Booster RF Cavity Review 29 September 2015 Summary
Paul Derwent

October 8, 2015

1 Executive Summary

A review was held on September 29 on the status and plan for a new Booster RF Cavity. The review charge, committee, and agenda are included in the following section. I asked the committee members to submit an individual report – these reports are appended. This section is a brief summary from my reading of those reports.

The reliability of the refurbished 15 Hz Booster cavities is an open question. There are still components (e.g., the ceramic window) that may be expected to fail. However, the refurbishment process gives confidence that future failures will be surmountable. In addition, the plan to build 2 more cavities (reach 22 operational) gives additional operational performance overhead. In the end, the reliability question is such that all recommend pursuing new cavities, especially in the context of operations for PIP-II.

The cavity specifications, as presented at the review, should work well for PIP-II with the cavities operating in the Booster. For a future PIP-III era (a new RCS), the RF specifications are valid but the committee felt that a larger bore would be required. 5 inches was suggested. We probably need to discuss this with Valeri to get more input on aperture requirements. He was comfortable with a 3 inch aperture.

The committee felt the simulation efforts on both the parallel biased and perpendicular biased cavity (for the 2nd harmonic) show promise and that the design team is proceeding in the correct direction towards a technical design. All members thought we should proceed with building prototypes of both parallel (53 MHz) and perpendicular (106 MHz) biased cavities. There was a split on the followup, some suggested going with the parallel bias design as the default while others suggested waiting to see if the problems with perpendicular bias (mainly the heating of the garnet) could be solved.

There were several other useful comments to the design team (and management) that we should follow up on. We should follow up on expanding the project team (especially in the context of detailed engineering design) with defined responsibilities to keep progress focussed and on point for the next year.

2 Review Details

The Proton Improvement Plan is pursuing design of a new RF cavity for the Booster. This cavity would be used in the Booster during the PIP and PIP-II operational eras, covering the 2020-2030 time frame. With replacement of the Booster under discussion (PIP-III), a third set of beam requirements is also under consideration.

Given the three sets of requirements, the PIP team has put together a technical specification and concept for a new cavity design. The purpose of this review is to evaluate the concept and ask if the cavity performance specification forms a suitable basis for proceeding to technical design. The results of this review will provide support for the PIP team in pursuing the RF cavity development.

We would like the committee to address the following questions:

1. What are the limits for using present cavities in the Booster? In particular, what is the expected reliability of refurbished cavities for the next 10-15 years, and what are the limits for the beam current and rf voltage amplitude with beam loading. What kind of problems shall we expect if these cavities are used for PIP-II (20 Hz repetition rate and 6.4e12 protons extracted)?

2. Do the requirements and concept of new cavities correspond to the present Booster operational needs and PIP-II Booster upgrade? Can these new cavities be used for a future RCS supporting 2 MW operation of MI?

3. Is the team proceeding in the correct direction towards a technical design?

The review committee consisted of:

- Ioanis Kourbanis, AD/Main Injector
- Brian Chase, AD/RF
- Ralph Pasquinelli, AD/PIP-II
- Timergali Khabiboulline, TD/SRF

The review was held on 29 September and is in the Beams Document Database. Agenda and presentations can be found at https://beamdocs.fnal.gov/AD-private/DocDB/DisplayMeeting?sessionid=112.

PIP RF Cavity Review Report

September 29 2015

Ioanis Kourbanis

Charge Questions:

I ask each member of the committee to answer the following questions:

1. What are the limits for using present cavities in the Booster? In particular, what is the expected reliability of refurbished cavities for the next 10-15 years, and what are the limits for the beam current and rf voltage amplitude with beam loading. What kind of problems shall we expect if these cavities are used for PIP-II (20 Hz repetition rate and 6.4e12 protons extracted)?

Even the Booster cavities have been re-furbished to allow them to run at 15 Hz they still are old and we should expect more things to fail (like the ceramic windows and the end flanges). In the PIP plan 22 total rf cavities will be installed giving an operational margin of 4 cavities (1100KV compared to 900 KV). This margin should be sufficient for the 700 KW complex operations.
For PIP-II Booster will be required to run with 50% more beam (6.4e12p instead of 4.3e12p) and at 20 Hz rep rate instead of 15 Hz. Even if we assume that the min bucket area required with 50% more beam is the same as the current one (with 900 KV) a total of 1100 KV of rf voltage will be required. This leaves no operational margin and will lead to down time and reduction of intensity. Running 50% more intensity will require about 10 db of rf feedback in order to be Robinson stable. There is no issue with the rf power.
New rf cavities with increased reliability and more rf voltage (at least 10%) will be required in the Booster for PIP II. Adding a second harmonic to the 20 Hz ramp will add a few (~5 msec) to the acceleration period but it will reduce the peak rf power delivered and will reduce the peak voltage requirements.

2. Do the requirements and concept of new cavities correspond to the present Booster operational needs and PIP-II Booster upgrade? Can these new cavities be used for a future RCS supporting 2 MW operation of MI?

The requirements and concept (parallel biasing) of the new cavities will satisfy the needs for PIP II.
The 3 inch aperture chosen for the new cavities is too small for a new RCS required to accelerate 3e13 protons to 8 GeV from 1-2 GeV. A cavity aperture of at least 5 inches will be required for the PIP III RCS.

3. Is the team proceeding in the correct direction towards a technical design?

The PIP team is developing a new cavity design (with parallel biasing) that incorporates the "lessons learnt" from the current cavities. In the perpendicular biasing cavity design there are issues with the ferrite cooling that need to be addressed. In the second harmonic cavity the heating of the ferrites is reduced by limiting the cavity on times (duty factor).

In addition, please include comments and recommendations for the PIP group.

Comments:

Recommendations:

1. **Develop a parallel biasing cavity design optimized to PIP II frequency sweep (44.7 -53 MHz) with a 5 inch aperture.**
2. **Consider adding a second harmonic to Booster 20 Hz ramp.**

PIP RF Cavity Review Report

September 29 2015

Brian Chase

Charge Questions:

I ask each member of the committee to answer the following questions:

1. What are the limits for using present cavities in the Booster? In particular, what is the expected reliability of refurbished cavities for the next 10-15 years, and what are the limits for the beam current and rf voltage amplitude with beam loading.

   Simulations show that for 15 Hz operations, about 1 MV is required and the current cavities can easily reach this voltage as well as the higher voltage requested for current operations. Beam loading is really an amplifier question for available power and as I understand this is not an issue. Reliability will continue to be a problem but should be less with the additional cavities that are being installed, as there should be more tolerance for single failures. There are no failure modes that have been identified that are unfixable with the current cavities. Therefore, for at least as this question is concerned, it appears that applying lessons learned to all new repairs and taking time to make quality repairs can allow current be sustainable for many years. However, data was not shown concerning the cost effectiveness of repair or if new cavities would be more cost effective.

   What kind of problems shall we expect if these cavities are used for PIP-II (20 Hz repetition rate and 6.4e12 protons extracted)?

   The higher dp/dt of the 20 Hz rep rate will require higher accelerating voltage. This is offset by the higher injection energy which requires less bucket area. C. Bhat's simulation show a higher acceleration phase angle and 1.1 MV from the cavities. This is still in reach of the current cavities but the head room is reduced creating more reliability issues. It is also likely that the current cavities will become hotter(activation) or will just become the source of a cap on beam intensity because of the small aperture.

2. Do the requirements and concept of new cavities correspond to the present Booster operational needs and PIP-II Booster upgrade?

There are several improvements that are proposed that should increase the operating voltage, reduce the average power loss and improve reliability. This will cover and potentially improve present operations.

PIP-II operation at 20 Hz with new cavities appears to be covered by the parallel bias cavity design. Higher voltage, lower loss and a larger aperture are all in the right direction. However, it is not clear that there will be enough voltage headroom to tolerate station losses. Moving forward with a cavity prototype and a continued simulation effort would answer this question.

3. Can these new cavities be used for a future RCS supporting 2 MW operation of MI?
   I listened to the debate on this issue, but have no direct involvement in calculation or study. I will just repeat Ioanis's comment that all recently designed machines have a 5" beam pipe and bore. Due to the current focus on low beam loss in machines a large bore seems to make sense. Again, out of my field of expertise.

4. Is the team proceeding in the correct direction towards a technical design?
   Designing something close to the current cavity makes sense and , it is pretty clear that there are substantial improvements that can be made.
   I would like to see two clearly separated designs, one that would cover 37 to 53 MHz and one that would cover 44 to 53 MHz for parallel biased cavities.   Any work on a perpendicular biased cavity should wait for results from the 2nd harmonic cavity in operations. Again here I would focus on the 44 to 53 MHz range.

   A lead engineer and design team was not clearly identified for a project of this scale. The plan for manufacturing of 20 plus cavities needs to be determined early in the process or the design process will be repeated.

In addition, please include comments and recommendations for the PIP group.

Comments:

It may be that $20M could be spent on new cavities and the Booster would operate much as it does today. There are many weak areas of this machine and fixing a few will only lead to the discovery of the next weakest link.
Presently there a substantial gap between operational RF voltage and the RF voltage required in simulation. Without agreement with simulation, operation parameter setting become heuristic and the path forward becomes cloudy.

One thing we can say is that there are clear limitations of the preset RF control system as there is only station by station regulation and no global regulation of the two RF cavity groups. When a cavity trips during a ramp, other cavities are not requested to make up for the lost voltage. Because of this, the voltage request curve is set higher than what is optimal for acceleration and emittance preservation. The implementation of the Mid-level RF controller in the Main Injector made for a much smoother operational machine. There are also many limitations to the control architecture that makes the design and implementation of studies somewhere between difficult and impossible. Frankly the Linac/Booster control structure needs the attention of a green field design effort. Incremental improvements to instrumentation or other subsystems will not and cannot change the architecture. Presently there is an incredible amount of daily tuning that goes on in these machines draining resources. The installation of quality feedback and control systems could pay for itself in short order freeing up manpower for other important tasks.

Recommendations:

Yes, pursue the new cavity design, but bring the design team up to critical mass before too long. This probably means getting a bigger involvement from TD.

At the same time pursue the upgrade and new development of beam-based instrumentation, feedback and control. This could be part of the PIP or there may need to be a new task force for this effort. This should have a goal of measuring and controlling the emittance from machine to machine in a structured and preferably automated fashion.

PIP RF Cavity Review Report

September 29 2015

Timergali Khabiboulline

Charge Questions:

I ask each member of the committee to answer the following questions:

1. What are the limits for using present cavities in the Booster? In particular, what is the expected reliability of refurbished cavities for the next 10-15 years, and what are the limits for the beam current and rf voltage amplitude with beam loading. What kind of problems shall we expect if these cavities are used for PIP-II (20 Hz repetition rate and 6.4e12 protons extracted)?

Recently refurbished booster cavities operate at 15 Hz currently for less than 0.5 year. Increasing repetition rate lead to increased RF losses in the cavity and maximum temperature. As a result lifetime may reduce and fail rate increase. Therefore replacement cavities should be developed.
20 Hz operation is acceptable for current beam current if injection energy increased to 800 MeV or higher. More beam current will lead significant increasing of beam losses and new cavity with larger beam aperture is needed.

2. Do the requirements and concept of new cavities correspond to the present Booster operational needs and PIP-II Booster upgrade? Can these new cavities be used for a future RCS supporting 2 MW operation of MI
    a. What is current for 2 MW

Requirements for present Booster operational needs and PIP-II Booster upgrade are demonstrated. But beam loss analysis is preliminary.
Concept design of future cavities development is in beginning status. Design work should be finished and prototype cavity manufactured and tested.

3. Is the team proceeding in the correct direction towards a technical design?

Overall yes. Second harmonic cavity manufactured and tested in order to demonstrate feasibility of perpendicular biased cavity.

In addition, please include comments and recommendations for the PIP group.

Air filter should be installed for cavity cooling air lines.

Notes from Booster PIP cavity review September 29, 2015

Ralph J. Pasquinelli

The presentations consisted of work on the refurbishing of the existing cavities, preliminary design of perpendicular biased ferrite cavities, and a second harmonic cavity based on perpendicular biased cavity. There was little to no mention of schedule, priorities, or budget in the review. While knowing the schedule and funding is essential to choosing a technology for the future, this review was based solely on technical issues.

There is little doubt that the booster will need to be in operation for at least the next 20 years. Also, the intention is to run at 15 Hz to meet the proton needs of the physics program. While the booster has recently been shown to operate at 15 Hz, an extended run has not yet been completed. When the accelerator complex comes back to life over the next few weeks, the proving grounds will be at hand. It is prudent to pursue the improvements or replacement of the RF cavities as they are becoming frail and have seen a lot of damage over their lifetimes. The increased beam current may also make for more radiation damage, which is an operational hazard. A larger aperture cavity should be examined at some point before a decision is made for complete replacements. The extended run at 15 Hz will provide clues.

There have been many lessons learned and re-engineering of the existing parallel biased booster cavities. After some forty years of operational history, it is a proven technology, but a great deal of engineering and examining construction techniques of tuner production and cooling issues has successfully been addressed. A plan now exists to build a brand new parallel biased cavity will all new components. This will retain a 3-inch aperture, which is commensurate with the existing booster accelerator. For the long term future of the Lab, a new rapid cycling synchrotron may be in order (PIP3?) and a 3-inch aperture cavity may not be appropriate, this time line could certainly be two decades in the future. I agree that a new cavity should be built and installed in the booster to operate at 15 Hz with 20 Hz capabilities. If operationally successful, this will provide a low risk means of replacing equipment that will be getting to the half-century mark of operations. But this solution may not satisfy the needs for a new synchrotron.

That being said, I suggest holding off on the manufacture of multiple parallel biased cavities until a complete design and costing for a perpendicular biased cavity has been completed. If funding allows for a prototype of such a cavity, it should also be fabricated and installed in the booster. More than likely, PIPII will not be commissioned until the year 2025. In my opining, having 10 years to develop a solution for replacing the booster RF hardware is ample time for the R&D.

If all of the above work could be finished in the next five years, a re-evaluation of the next step would be in order. Should the design remain with 3-inch aperture, or should 5-inch aperture be specified. Certainly all of the work done to that point will be most useful to the larger aperture design. There is a trade off between copper costs and garnet cost. In the end, price most likely will dictate the direction to be taken.

Designing and building the second harmonic cavity should proceed realizing that a simpler solution may be to make two different second harmonic cavities, one for injection the other for transition, providing there is space in the lattice for both. Lessons learned from this cavity design can be applied to the design of the fundamental perpendicular design.

All of this will require a steady dedication of resources. So far, the team in place has done an excellent job, so keeping it intact is essential.