26 April 2017

Report from the 5th Meeting
of the PIP-II Machine Advisory Committee (P2MAC)

April 10-12, 2017
Fermilab

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1. Introduction

The fifth meeting of the PIP-II Machine Advisory Committee (P2MAC) took place on April 10-12, 2017, at Fermilab with the agenda shown in Appendix 1.

All Committee members were present, namely: Rick Baartman (TRIUMF), Roland Garoby (ESS - chair), Frank Gerigk (CERN), Kazuo Hasegawa (JAEA, J-PARC), Sang-Ho Kim (ORNL, SNS), Deepak Raparia (BNL), Jie Wei (MSU, FRIB), Hans Weise (DESY).

The P2MAC is grateful to the speakers for the quality of their talks and to the organizers and the Fermilab management for the quality of the organization. The Committee members appreciated the early availability of the information for this meeting (CDR and talks) which greatly help preparing.

The Committee took note with satisfaction that its past recommendations had been taken into account.

The Charge to the Committee during this meeting is to provide advice, recommendations, and/or commentary on 4 questions (Appendix 2). The P2MAC responses and main recommendations are included in the executive summary (section 2). The detailed findings and observations, which lead to these recommendations, are detailed in the second part of this report (section 3).

2. Executive summary

General observations and comments

The goal of PIP-II is to support long-term physics research goals as outlined in the P5 plan, by delivering world-leading beam power to the U.S. neutrino program and providing a platform for the future. A proton beam power of the MW-class over the energy range of 60-120 GeV has to be delivered by the time of first operation of the new long-baseline neutrino facility (LBNF), planned 21 months after Q3FY24. In the longer term, PIP-II should also provide the possibility to progress towards higher beam power from the Main Injector (>2 MW) as well as to upgrade the Mu2e experiment by delivering a continuous beam at 800 MeV.

The proposed PIP-II project is based on the following components:

- A new 800 MeV superconducting H- linac, constructed of CW-capable components, and initially operating in pulsed mode to inject in the booster at twice the present energy to increase by 50% the intensity per pulse,
- Increasing the booster cycling rate from 15 to 20 Hz,
- Increasing by 50% the intensity per pulse from the Recycler and the Main Injector.

An ambitious R&D program is ongoing jointly with four DAE laboratories in India with the goal of minimizing/mitigating risks during the construction phase of PIP-II.
For the linac, the PIP-II Injection Test (PIP2IT) set-up is an essential part aimed at testing/demonstrating the low energy front end, the HWR section, the first SSR1 cryomodule as well as multiple other equipment and software. In addition, HB650 cavities are being prototyped

and a complete cryomodule with 6 cavities is being developed. Prototypes of solid state power amplifiers have to be built and tested in India and later in Fermilab.
For the existing rings, a combination of simulation and beam tests is being used to confirm the feasibility of the performance goals. Hardware upgrades (e.g RF in the Main Injector) and new equipment have to be designed and built (gamma-t jump in the Booster, collimators in the Recycler…).

Progress has been remarkable in 2016, with the following main achievements:

- Analysis of Alternatives submitted to DOE in July 2016 and preferred alternative identified in January 2017 (CW, superconducting linac),
- Agreement with INFN/Milano for contributing 2 prototype LB650 cavities,
- Positive outcome of DOE Independent Review of PIP-II (November),
- A new transverse damper in the Recycler which has allowed to reduce beam loss during slip-stacking and contributed to the new record beam power of >700 kW on the NuMI target
- Installation and operation of the RFQ in PIP2IT where pulsed beam tests are regularly taking place.
- Experimental demonstration of the stabilization of the tune of a cold SSR1 cavity in pulsed mode within a factor of 2 of the design goal.

A first draft of the PIP-II Conceptual Design Report has been prepared and submitted to the Committee at the beginning of March. The final version of this CDR is the main deliverable for getting CD-1 approval during the fall of FY17.

Comment

- The Committee congratulates all contributors for the good progress in 2016, on the technical as well as on the management fronts.
- The presence of new presenters/younger staff is noted and acknowledged as a welcome sign for a project that will materialize and expand during the next decade.
- The risks associated with the dependence on external/international partners to continue progressing in developments and to proceed with construction deserve proper evaluation and adequate mitigation must be foreseen.

Responses to the Charge questions

Q1: *Is the scope of the facility described in the CDR both feasible and likely to satisfy the requirements outlined in the Mission Need Statement?*

YES.

According to the PIP-II FRS (ED0001222), "The Mission Need Statement (MNS) for PIP-II represents the implementation of the P5 plan by the Department of Energy. The MNS identifies two primary goals:

1. To reduce the time required for LBNF/DUNE to achieve world-first results.
2. To sustain high reliability operation of the Fermilab complex.

The MNS establishes 1.2 MW as the goal for beam power delivered from the Main Injector following implementation of PIP-II. The MNS also describes the need to implement PIP-II in a manner that will allow a subsequent doubling of power delivered from the Main Injector based on future upgrades, and the desirability of maintaining compatibility with a subsequent upgrade to continuous wave (CW) operations in support of a broader spectrum of particle physics research opportunities, including muons."

It is clear to the Committee that the scope of the facility described in the CDR is precisely tailored to these medium and long term goals.

Multiple studies together with experimental investigations with the existing accelerator complex as well as PIP2IT are being conducted in preparation of PIP-II. They have reached a degree of maturity which makes the Committee confident that the foreseen beam performance will be attained after PIP-II, and that further progress will be within reach with additional upgrades (doubling of beam power from the Main Injector, support of experiments with high duty factor …).

Q2: *Is the facility likely to meet the enumerated performance goals incorporated into the Functional Requirements Specification (FRS).*

YES.

The Functional Requirements Specifications (FRS) define how Linac, Booster, Recycler and Main Injector are planned to operate and what their performance have to be to meet the scope of PIP-II.
For the existing accelerators, performances are extrapolated from their present status, based on beam experiments and simulations. For the linac, the estimated performance is based on prototypes of critical equipment (e.g. SSR1 and HB650 cavities) and on results at PIP2IT. The Committee considers that the data available convincingly indicates that all accelerators as well as the whole facility will meet the enumerated performance goals.

Q3: *Have the risks inherent in the conceptual design been adequately identified and appropriately targeted within the R&D program?*

YES, but…

A project like PIP-II that aims at increasing the performance of 3 existing well-optimized accelerators and the construction of a new state-of-the-art linac necessarily entails significant risks which require a wide range of prototypes and tests to be retired. The Committee agrees with the priorities selected by the project management and acknowledges the remarkable results and progress on multiple fronts: SSR1 and HB650 cavities, control of cavity tune in pulsed mode, high intensity in the Booster, reduced loss during slip-stacking in the Recycler thanks to a new transverse damper…
However other prototypes will also be necessary like SSR2 and LB650 cavities, complete cryomodules for SSR and elliptical cavities; more work is needed to increase confidence in reliability of piezo devices, RF couplers etc. and technical design is necessary for the injection girder in the Booster.
Risks associated with procurement of high technology devices should not be underestimated.

Q4: *Can the conceptual design be characterized as being sufficient to provide the technical basis for CD-1?*

YES.

As it stands, the conceptual design is supported by convincing results of studies and experimental tests that provide a sound technical basis for CD-1.

Recommendations

R1: R&D activities should be managed in a timely manner so that all critical risks are mitigated prior to the target date of CD-3.

R2: Consider the addition of a low power beam dump in a straight section at the end of the linac tunnel for beam tuning/study.

R3: Scheme for the energy stabilization, the requirement of LLRF system, and associated hardware design should be carefully analyzed as a whole.

R4: Flesh out and finalize the Booster injection girder design.

R5: In Recycler and MI, optimize beam collimation in all phase space dimensions and evaluate potential benefits, including momentum collimation in the beam transfer lines and horizontal collimation in Recycler.

R6: Develop milestones for hardware upgrade R&D including Main Injector RF system design down-selection and Recycler new 53 MHz RF cavity design.

R7: Benchmark and maintain computer simulation codes used for beam dynamics designs in synchrotrons.

R8: For the linac, the PIP-II plan is based on the contribution of high technology components from partner institutions which are still in the learning phase. Investigate resources needed on the U.S. side to successfully transfer knowledge and technology; cost and schedule risks need to be minimized.

R9: The Committee strongly recommends imposing a common standard for RF amplifier control interfaces & electromagnetic compatibility. This will help to avoid the use of significant Fermilab manpower for adaptations and corrections on delivered equipment.

R10: Validate the long-term reliability of the microphonics and LFD compensation hardware within the PIP-II R&D program.

R11: Foresee long-term testing of all RF couplers under PIP-II operational conditions.

R12: Implement anticipated control systems modification required to support PIP-II operations, including the MPS, into the PIP2IT program as soon as is reasonably achievable.

3. Complementary observations and reactions

3.1 Linac warm front end

Findings:

- The Warm Front End (WFE) consists of two ion sources funneling into a 2 meter long partially neutralized LEBT, followed by a 162.5 MHz, 4.4 meter long, 2.1 MeV RFQ and a 14 meter long MEBT.
- The WFE is designed to provide an average beam current of 2 mA (pulse length 10 μs to CW) with transverse emittance ε_n, rms <0..23 mm.mrad and longitudinal emittance ε_n, rms <0.28 mm.mrad.
- The MEBT houses a beam chopping systems capable of bunch-by-bunch selection, sets of scrapers, 21 kW beam absorber, and beam diagnostics.
- The MEBT was recently extended by 3.5 meter to provide sufficient time for a fast vacuum valve to protect the SRF cavities in case of absorber vacuum failure and to provide space for a radiation protection wall.
- Thanks to this shielding wall, the warm front-end will be available for public viewing.
- The partially neutralized LEBT operation with low emittance growth was demonstrated in the PIP2IT.
- The RFQ was tested for CW operation during 300 hours until each power coupler window developed a small leak. Since then the RFQ operates only in pulsed mode.
- The measured emittance out of the RFQ is ε_n, rms ≤ 0.2 mm.mrad (x & y) for 1 – 5 mA.
- The ion source still exhibits a slow beam current drift and this is presently mitigated by 3 feedback loops

Comments:

- Successful demonstration of partially neutralized LEBT operation with low emittance growth was noted.
- Extending the MEBT by 3.5 meter and adding one more buncher should have adverse effects on longitudinal particle distribution, but simulations show no increase in beam loss due to the extended MEBT. We encourage revisiting simulations including all errors.
- A cold trap in the form of a cold section of beam pipe before the HWR section may help to: i) minimize particle migration from the warm MEBT and absorber into the SRF section, and ii) slow down a pressure wave due to an accidental vacuum leak in the MEBT.
- PIP2IT commissioning is underway and has not yet mitigated all the risks, in particular, reliable CW operation of RFQ, bunch-by-bunch selection, MEBT absorber compatibility with SRF, and reliable operation.
- We encourage around the clock operation of PIP2IT for long period of time to investigate further the ion source drift and to establish reliable operation.

3.2 Superconducting linac

Findings:

- Linac alternatives were considered. The Alternative 1 (reference design, a CW capable superconducting linac) was chosen. Justifications for this decision are 1) it will provide significant long-term opportunities and 2) it can be realizable at a cost comparable to the other alternatives under the currently envisioned assumption on in-kind contributions from international partners.
- Overall, the team made substantial progress since last review aligned with CD-1 preparation, although there are some challenges ahead. The linac scope has not changed since last review. The overall linac design is solid and the R&D items are identified for reaching the performance goals. Due to constraints in available funding and resource, schedules of some R&D items are rearranged through prioritization process. All identified R&D activities will be completed by 2020 prior to the current target date for CD-3 with the possible exception of the final testing of the prototype HB650 cryomodule.
- Optics for the PIP-II SCL is designed. In a nominal operational condition, intra-beam stripping is identified as the major source of beam loss in the superconducting linac (SCL). The losses due to intra-beam stripping are estimated to be less than 0.1 W/m for the entire SCL. It is described in the CDR that fixed aperture beam collimators will be installed between each cryomodule for HWR, SSR1 and SSR2. The thickness of the collimator at the end of SSR2 section is 4 cm of steel. There are no dedicated collimators in the elliptical region.
- Potential compensation schemes for various fault scenarios are analyzed. The 'local compensation' scheme demonstrates that the SCL can be retuned for the selected fault scenarios.
- The Linac tunnel has space reserved to accommodate four additional HB650 cryomodules. The transfer line to the Booster is conceptually designed. The transfer line accommodates a switchyard located between two arcs. The switchyard houses a fast kicker and a three-way septum magnet for the linac beam dump, Booster and Mu2e. For high quality injection into the Booster, beam energy stability should be better than 0.01%. The linac dump line will be used as a part of linac energy stabilization system. Beam energy will be measured by time-of-flight measurement using BPMs. The impacts of LLRF phase/amplitude error and beam loading on the beam energy are presented.
- Five types of cavities were chosen with various considerations. Design for HWR, SSR1 and HB650 cavities is completed and final optimization for SSR2 and LB650 cavities is in progress. Design of the HWR cryomodule is completed, and fabrication is ongoing, aiming at cryomodule commissioning in 2018. SSR1, SSR2, LB650 and HB650 cryomodules will share a similar mechanical design, piping and instrumentation. Lesson learned from LCLS-II cryomodule will be incorporated in order to reduce the movement and vibration on the two-phase helium pipes. SSR1 cryomodule design is in the final state (90% completion) and fabrication will be completed by the first half of 2019. The preliminary design of HB650 cryomodule is done and the final design efforts will follow after the SSR1 cold-mass final design.

- Analysis shows that non-negligible quadrupole field exists in HWR, SSR1 and SSR2 cavities due to asymmetric nature of EM field in these RF structures. Since SSR1 and SSR2 cavities are rolled by 45 degree, their quadrupole field becomes skew quadrupole field. The skew quadrupole field will be compensated by imbalanced powering of the vertical and the horizontal correctors.
- Control algorithm for active LFD compensation is being developed and its test with a dressed SSR1 cavity is in progress. The extended testing time has been allocated for this activity. Currently σ~7 Hz rms detuning is achieved in open loop. It is presented that there's room for further improvement. The goal is to achieve cavity detuning less than 20 Hz peak (σ~3 Hz) in presence of microphonics and LFD.

Comments:

- It is found that the overall progress on the design of the technical scope is consistent with the baseline. The baseline design supports meeting the PIP-II performance goals.
- International collaboration remains a critical part of the PIP-II project. It could affect the project cost, equipment performance and R&D/project schedules.
- It is noticed that some of R&D activities are delayed. It is a concern since one R&D item could affect other R&D items and consequently delay the final design of the critical components.
- Vendors who fabricated the old version of HB650 cavities went out of SRF cavity business. Supply chain or collaboration partner for prototype cavities (SSR2, LB650 and HB650) need to be developed. Continued effort is required to keep the supply chain in a healthy condition.
- The preliminary result of LFD compensation is encouraging. The plan to continue a comprehensive test is viewed by the committee as an essential investment for the success of the PIP-II project. Developing a solid resonance control scheme for pulsed operation of four different types of cavities is still very challenging.

Recommendations:

R1: R&D activities should be managed in a timely manner so that all critical risks are mitigated prior to the target date of CD-3.

R2: Consider the addition of a low power beam dump in a straight section at the end of the linac tunnel for beam tuning/study.

R3: Scheme for the energy stabilization, the requirement of LLRF system, and associated hardware design should be carefully analyzed as a whole.

3.3 Booster

Findings:

- To meet the PIP2 goal of 1.2MW at 120GeV, the Booster will be required to accelerate 6.5e12 protons per pulse, and the pulse rate is to be raised to 20Hz. Simulations indicate that it will be difficult to exceed 7e12 protons per pulse. For this reason, any further upgrade beyond 1.2MW requires a replacement 8 GeV accelerator.
- The new 800MeV injection energy will alleviate space charge, but the CW 2mA limit requires much enlarged injection window of 600 μsec, 15 times larger than present.
- The new injection scheme requires phase space painting and therefore ramping of the magnets over this time window. The higher injection energy requires the magnets to have lower fields, and they are therefore longer. The injection straight has yet to be designed.
- The longitudinal beam-coupling impedance is known to be large in the Booster because the beam is exposed directly to the laminations of the 48 AC dipoles. It has recently been both calculated and measured and these agree fairly well.
- RF cavities and their tuners have gone through a major upgrade in the context of PIP. As well the number of cavities has increased from 18 to 22 stations. These are capable of at least 50kV each, so 1.1MV is now possible.
- Transition Q-jump as presently practiced has shown both in tests and in simulations, to be adequate.
- Simulations indicate around 2-3% of particles are outside the intended longitudinal phase space at extraction.

Comments:

- The new injection girder concept is a very tight fit in the long straight. As the straight cannot be extended, and the dipole fields are strongly constrained, there is a risk that the 800 MeV injection energy has to be dropped slightly.
- The committee was impressed with the progress on understanding the longitudinal beam-coupling impedance and the implications upon the beam's behavior. It has a large real part and so dissipates some of the beam energy and this has to be provided by the RF cavities.
- One RF cavity has been tested successfully at 20Hz tuner cycling. But there is a dividend from running at 800MeV injection since the frequency swing is smaller. So the committee judges that the 1.2MV needed for PIP-II is reasonable with the existing RF cavities.
- The longitudinal tail of the Booster-extracted bunches is to be mitigated by collimation. See Comment under Main Injector/ Recycler Ring section.

Recommendation:

R4: Flesh out and finalize the Booster injection girder design.

3.4 Recycler and Main Injector

Findings:

The PIP-II scope corresponding to the Recycler and Main Injector include

- Upgrades to the Recycler to accommodate slip-stacking of 7.7×10^{13} protons delivered by twelve Booster batches,
- Upgrades to the Main Injector to accommodate acceleration of 7.5×10^{13} protons per pulse to 120 GeV with a 1.2 second cycle time, and to 60 GeV with a 0.7 second cycle time.

Specifically, PIP-II performance goals relative to the present PIP performance include

- Main Injector protons per pulse (extracted) from 4.9×10^{13} to 7.5×10^{13} ,
- Main injector cycle time at 120 GeV from 1.33 to 1.2 sec,
- Beam power at 120 GeV from 0.7 to 1.2 MW,
- Operating Main Injector at energies as low as 60 GeV with cycle time of 0.7 sec and beam power 1 MW.

Hardware upgrades identified to meet the performance goals include

- Main Injector RF power increase of about 20% by one of the following options,
    - Operate the current RF cavities with two power tubes instead of one in a push-pull configuration. This will require doubling of the number of modulators and solid-state drivers.
    - Use a new more powerful power tube, such as the EIMAC 4CW250,000B. This will require a new mounting configuration (to accommodate the much longer tube), new modulators, and upgraded power amplifier cooling.
    - Replace the entire RF system with a new one (new cavities and PAs). The advantage of this solution is that it can accelerate enough intensity to reach 2.3 MW in the next round of Accelerator complex upgrade.
- Recycler new 53 MHz RF cavity system operating at CW for 140 kV voltage.
- Transition jump system consisting of 8 sets of pulsed quadrupole triplets along with needed power supplies and controls.

Beam dynamics and accelerator physics studied performed include

- Recycler slip stacking gymnastics with space charge using Synergia codes,
- Transition crossing with a 1st order matched jump with ESME codes simulation of the longitudinal phase space including chromatic nonlinearities and collective fields,
- Collective effects including space charge, longitudinal coupled bunch instability, transverse single-bunch head-tail instability, transverse coupled instability due to wall resistivity,
- Electron cloud effects and mitigation with beam scrubbing and secondary emission yield control.

Recycler collimators were installed during the summer shutdown. During operations, the collimators reduce uncontrolled beam loss in the vertical direction, localizing beam loss to the collimator region and abort region. New Recycler “frequency” damper was commissioned allowing to damp the resistive wall instability and to maintain low chromaticity through slip stacking.

Comments:

- The scope of the facility described in the CDR is feasible and likely to satisfy the requirements outlined in the Mission Need Statement. Performance goals are appropriately developed based on the current performance of Recycler and Main Injector to meet PIP-II project requirements. The facility is likely to meet the enumerated performance goals incorporated into the Functional Requirements Specification (FRS).
- Instabilities appear now to be well-understood. In particular, the inability of the bunch-by-bunch transverse dampers to damp instability during slip-stacking in RR is understood and a new "frequency" damper has been successfully commissioned. The result is that slip-stacking can proceed at low chromaticity with greatly reduced beam losses.
- Transition crossing with a 1st order matched jump has been designed for the past 15 years and is most likely to be effective in preserving longitudinal beam quality with minimum perturbation to the transverse motion. The conceptual design is to be followed by engineering design and prototyping of the pulsed magnet system.
- Slip-stacking 50% more intensity in the Recycler requires a reduction in fractional beam loss from 5% to 3% during the stacking process. It would be beneficial to study the potential gain in optimizing beam collimation in not only vertical but also horizontal and longitudinal directions to reduce uncontrolled beam losses.
- Options to renovate the Main Injector RF system are presented with an estimated evaluation time of about 2 years. We urge the project team to start necessary R&D that can lead to down selection of design choices before the project baseline.
- Design of a new RF cavity with higher R/Q and active beam loading compensation for the Recycler is estimated to take about 2 years before prototype tests may start. We urge the project team to develop milestone to track the design and development progress.
- Computer simulation code ESME has continuously been used without maintenance for transition crossing studies. A six-dimensional code Synergia has been developed and used for slip-stacking and transition crossing simulations taking into account space charge and chromatic effects. As PIP-2 design relies on these codes, we urge the project team to benchmark these simulation codes both with other codes and with machine study results.

Recommendations:

R5: In Recycler and MI, optimize beam collimation in all phase space dimensions and evaluate potential benefits, including momentum collimation in the beam transfer lines and horizontal collimation in Recycler.

R6: Develop milestones for hardware upgrade R&D including Main Injector RF system design down-selection and Recycler new 53 MHz RF cavity design.

R7: Benchmark and maintain computer simulation codes used for beam dynamics designs in synchrotrons.

3.5 Cryomodules and cryogenics

The layout of the cryogenics depends strongly on the design of SRF cavities, but also on RF couplers, and the chosen cryostat. The respective cryogenic related issues are treated in the following sections.

Findings:

Cryogenic issues related to SRF cavities

- PIP-II plans are based on high Q_0 cavities, the highest being the 650 MHz elliptical ones aiming for 3×10^{10}. The project strongly profits from the still ongoing work related to LCLS-II. The N-doping and N-infusion discovered in Fermilab were further elaborated and offer the effective reduction of cryogenic loads at 2K.
- Due to relatively small cryo-load the standard treatments are sufficient for HWR and SSR cavities in order to meet the PIP-II cryogenic specifications. This is not true for the 650 MHz cavities. A light N-doping is planned to be used but obviously still needs to be further optimized; the very high Qs predicted from 1.3 GHz cavity experience are not reached yet.
- Trapped flux sensitivity and flux expulsion studies give input for the specification of magnetic field shielding.
- The ongoing R&D program uses existing 650 MHz cavities treated with N-infusion. Results are expected soon. Work is continuing, and the expectations are that it will yield better results both high-Q and high gradient.
- The requirements for Q_0 values presented (M. Martinello, slide 6) are assumed to be conservative (A. Klebaner, slide 7); HB650 and $Q_0=3\times10^{10}$. Possibly achievable even higher Q_0 values may lead to a further reduction of cryogenic load.

Cryomodule (CM) design and production

- The design of the different CMs needed for all SRF cavities is based on the same idea: A strong-back will be used which is located at the bottom of the outer vacuum vessel, and kept at almost room temperature (285 K). The string of cavities is mounted on this strong-back and is precisely aligned. The cryostat is assembled around this prefabricated unit. Goal is to keep any movement of the aligned system within 10 µm. Since the SC linac consists of individual CMs which can be cooled down / warmed up independently, all process lines are closed at the module ends. The 2-phase line has end caps; longitudinal forces are taken by special rods mounted in parallel to the line.
- Each CM needs its own heat exchanger. The final design (review planned for June 2017) profits from the recent findings during the LCLS-II prototype module tests. The Helium filling into the 2-phase line was modified since the prototype tests suffered from micro-phonics due to thermo-acoustic oscillations. First LCLS-II modules with a modified He inlet will be tested in due time.
- The PIP-II design is based on the usage of high Q_0 cavities which require a fast cool down. The Helium process lines inside the CMs are designed accordingly. All He connections are welded; no flanged connections are used.

Cryogenic System

- The designed system will allow for full segmentation of the SC linac, i.e. the individual accelerator modules can be cooled down / warmed up independently. The plan is to make a replacement possible without lengthy shutdown.
- The design for both, pulsed mode as well as CW operation implies the need to cover quite different operating scenarios. The cryogenic load at 2K can vary from 700 W to 2.3 kW (with margin). The system needs to support cryogenic loads at various temperature levels (cavity, shields), and has to maintain stable pressure in order to minimize microphonics. The mentioned rapid cool-down and warm-up of cryomodules supporting the high-Q_0 values for the cavities is a must.
- The envisaged cryogenic system profits from actual developments for LCLS-II and the recently commissioned European XFEL. The latter has very similar specifications; the 2K design load is 1.9 kW, the achieved pressure stability is 0.03 mbar.

Comments:

Cryogenic issues related to SRF cavities

- Only some very few cavity vendors are currently able to follow the found recipes. In addition not all Niobium material available on the market (again some very few sources) shows the same reproducible behaviors. Flux expulsion obviously depends even on the production unit. Thus the successful production of the required high-Q cavities needs a good interplay between the cavity owner, holder of intellectual property, and the cavity producer. Only well qualified vendors can deliver the product needed. This may have some severe impact on the plan to 'outsource' an essential part of the cavity production to esp. Indian partner institutes.

Cryomodule (CM) design and production

- The 650 MHz CM design foresees large openings to access the frequency tuners. Both, the motor and the piezo tuners will need to operate over the full life time of the SC linac. Accepting the designer's preference for such openings, the envisaged maintenance should be exercised as part of the CM prototype test. It would be somewhat unlucky if a slightly increased opening diameter offered a better access or improved potential for interventions.
- The PIP-II team does not see the need for a 'crash test' i.e. an intentional beam line venting of a cooled-down prototype CM. There is some experience within the SRF community (ILC/XFEL modules) which should be used to support the decision to neglect such a test.
- The planned CM review (June 2017) should also include the discussion of alignment procedures. Transfer measurements will be needed as part of the procedure. The alignment at cold will be checked using internal wire targets and optical windows. Is a stretched wire system required to not suffer from challenges with offsets created by possibly misaligned windows? Such systems were used to verify other CM designs.
- Since CM repair scenarios are discussed, the needed dis- and re-assembly procedures should be documented and discussed in the frame of the planned CM review.

- The production of HB650 cavities is foreseen to happen at Indian partner laboratories. Since the CMs are high tech components, the technology transfer and the required Fermilab resources should not be underestimated.
- The plan to potentially remove a single module from the tunnel while all other neighboring modules are kept cold requires protection measures (rail or guiding system?). Do not risk the CMs isolation vacuum. Consider also some dedicated RF coupler protection scheme.

Cryogenic System

- The designed system considers different configurations in order to cope with the wide range of cryogenic load conditions. These different configurations were sketched, nevertheless the possible vendors – only two are known – need to come up with a strategy and proposals to fulfill the requirements. Answers from industry are expected in due time.
- The cryogenic 2K load margin used at other laboratories is of the order of 30%. The PIP-II design is using 15%. The absolute load numbers assume successful cavity R&D. The production of series cavities will require going for sufficiently experienced vendors.

Recommendations:

R8: For the linac, the PIP-II plan is based on the contribution of high technology components from partner institutions which are still in the learning phase. Investigate resources needed on the U.S. side to successfully transfer knowledge and technology; cost and schedule risks need to be minimized.

3.6 RF

Findings:

- *RF sources*: The solid-state RF sources for 162.5 MHz up to the HWR are procured in the US via FNAL, while the remaining amplifiers will be provided by India; 325 MHz by BARC and 650 MHz by RRCAT. The systems for RFQ and buncher 1 are installed and operational. Indian prototypes are under test in India, and a BARC 3 kW unit has been tested at FNAL in 2015. The prototypes from India have roughly 2x the size of Western produced units.
- *RF controls*: The amplifier control interfaces from different vendors and from India show big differences and need substantial rework at FNAL.
- *Circulators*: Circulators, which were bought from the cheapest suppliers showed major difficulties during tests. It was decided to increase the budget allocation.
- *Microphonics & LFD*: The combination of low beam current and high accelerating gradients yields large loaded Qs and a very narrow bandwidth. A mixture of passive and active measures is pursued to suppress microphonics and LFD. The goal is to keep the cavities within a bandwidth of 20 Hz (3 Hz 1 sigma), defined to limit the required RF power margin. A significant R&D effort was launched to suppress microphonics & LFD with tests on prototypes showing promising results.
- *Couplers*: Both RFQ coupler windows developed leaks after ~500 hours of operation in pulsed/CW mode with up to 65 kW. The nominal peak power specification is 75 kW. The coupler has been redesigned to have an exchangeable, larger, and thicker window, which will soon be tested. The committee is concerned about the use of O-rings for this redesign.
- *Vacuum*: The large hydrogen flux from the source and the strong outgassing from the MEBT absorber have been addressed adequately. Low-particulate vacuum practices are in place.

Comments:

- *Microphonics & LFD*: The expected ranges of uncompensated detuning of the various cavity types span more than one order of magnitude and should be studied more in detail. For this purpose, representative dressed test cavities of all types need to be available soon. The risks related to microphonics & LFD have been identified and an appropriate R&D program has been launched to master their suppression. Proof of principle tests have been carried out. Long-term testing needs to follow.
- *Reduction of cryo-load*: The scheme to use anti-phased RF during the cavity decay time increases the peak power in the couplers by a factor of 4. As the cryo-system is designed for CW, the risk of damaging couplers should outweigh a reduction of the cryo-load for pulsed operation.
- *Couplers*: test that the new LB/HB coupler with the inner copper liner can be assembled without creating/trapping micro-particles. Establish procedures for all production, assembly, qualification, and testing steps and make sure to document all of these.
- *Energy stability*: The goal of 0.01 % and 0.01 deg for amplitude and phase stabilization is two orders of magnitude stricter than for comparable proton machines. Verify if

these values are actually required for injection into the Booster and consider alternative schemes to reduce linac energy variations, e.g. to use a debuncher cavity with a fixed phase relation to the linac RF at a suitable distance from the linac end.

- *Transfer line*: The linac to Booster transfer line is designed to keep the magnetic stripping rate $<10^{-8}$ for a 1 GeV beam. As the linac has space for an energy upgrade to 1.2 GeV it would make sense to increase the magnet bending radius such that the stripping rate at 1.2 GeV is $<10^{-8}$.

Recommendations:

R9: The Committee strongly recommends imposing a common standard for RF amplifier control interfaces & electromagnetic compatibility. This will help to avoid the use of significant Fermilab manpower for adaptations and corrections on delivered equipment.

R10: Validate the long-term reliability of the microphonics and LFD compensation hardware within the PIP-II R&D program.

R11: Foresee long-term testing of all RF couplers under PIP-II operational conditions.

3.7 Beam instrumentation, Control and MPS

Findings:

Beam instrumentation

- Various beam instrumentation and diagnostics are necessary to characterize and monitor the beam parameters. Required instrumentation is prioritized with two categories for beam tuning:
    - minimum set: intensity, position/orbit, transverse profile, phase/timing and loss;
    - additional set: transverse emittance, longitudinal bunch profiling, transverse halo and chopping efficiency.
- The current work focuses on the development and test of instrumentation at PIP2IT in pulsed mode first, aiming at CW in a second stage.
- The BPMs at the MEBT have been operated and good performance (position resolution ~10 μm, phase resolution ~0.2deg) has been demonstrated. The TOF energy resolution has been ~0.3%, while expected value has been 0.1%.

Control

- The control system is responsible for control and monitoring of accelerator equipment, machine configuration, timing diagnostics, data archiving and alarms.
- The committee heard the requirements and general strategy of the control system. PIP-II will use an evolution of the Fermilab control system ACNET. PIP-II will therefore benefit from the large investment in software and hardware for this three-tiered system with front-end, central service, and user console layers.

MPS

- A Machine Protection System shall protect the linac and its components from direct beam induced damage and excessive radiation damage. The MPS inhibits the beam in case of excessive beam loss, equipment failures, or operator request.
- The MPS takes in signals from various sub-systems. These devices will be divided into primary and secondary categories based on how critical they are in mitigating beam damage.
- The system model is based on experience from the SNS accelerator. The MPS will consist of three layers; signal interface, FPGA based logic (permit system) layer, and actuator layer for beam inhibit.
- A drop of the beam permit will inhibit the linac beam at the entrance of the RFQ within 10 μs after the MPS receives the signal.

Comments:

Beam instrumentation

- The plan for beam instrumentation now properly encompasses the full linac and the transfer line.

- The progress of some devices' R&D such as a laser wire transverse profile monitor and resistive wall current monitor (listed in the additional diagnostics category) looks slower. The committee supports continued instrumentation R&D at PIP2IT to mitigate risks for PIP-II.

Control

- Most parts of the control system seem to be in the conceptual phase. Further consideration and work are needed to implement a new control system. A new timing system and increasing the Booster repetition from 15 to 20 Hz have to be developed and examined by the time of request. PIP2IT gives a framework to demonstrate before PIP-II operation. To mitigate the risk of PIP-II, scheduling and resource management in the PIP2IT R&D are important.
- Special attention needs to be paid to the timing in CW mode.

MPS

- A model of the MPS is based on the SNS experiences but special attention should be paid to the future CW operation. R&D is (or will be) carried out for FPGA logic system development, beam loss rate study, estimation of particle shielding of cryomodules, etc.
- Staged PIP2IT configuration requires the MPS to be expanded to accommodate new diagnostics, machine hardware and higher damage potential. The lessons learned from the MPS in PIP2IT will be transferred to PIP-II MPS and this transfer will mitigate the risk. But the committee has no information of the timeline for the PIP2IT MPS.

Recommendation(s)

R12: Implement anticipated control systems modification required to support PIP-II operations, including the MPS, into the PIP2IT program as soon as is reasonably achievable.

3.8 Radiation Safety and Conventional Facility

Findings:

Radiation Safety

- Design requirements and radiation limits for accelerators and beam transport lines are provided by the Fermilab Radiological Control Manual (FRCM). The beam condition and limit dose rete have been defined and shield requirements of linac, beam transport line, Booster, MI-8 line and Main Injector are shown.

Conventional Facility (CF)

- The conventional facility (CF) will house the accelerator components and support equipment. The location is driven primarily by the physics requirement and access to the existing infrastructure. The siting was chosen to minimize the impact to existing known wetland.
- The estimated total wall-plug power for linac and transfer line is 13.2MW, out of which the RF sources are dominant with an installed power of 8.3MW.
- Technical Design of CF is based on iterative discussions with stakeholders and the conceptual design will meet the requirements outlined in the Mission Need Statement. The review of risks related to the CF is underway. It has identified and targeted key risks to be addressed within the R&D program.

Comments:

Radiation Safety

- The presentation and the CDR properly cover radiation safety analysis, including the radiological design requirements for shielding, residual activation, air activation, water activation and radioactive contamination.
- Analysis of radiation safety helps formulate requirements to the conventional facility design. The analysis and documents will be updated in the radiation safety review processes.

Conventional Facility

- CF consists of site work, linac, transport line, cryogenics plant and mechanical plant. The CDR is sufficiently developed for these items and buildings. The committee congratulates the CF team for this work and considers that it provides the technical basis for CD-1.
- It should be expected that the layout and cross-section may be modified after more detailed consideration of installation, commissioning, operation and maintenance scenarios. Close interaction with the machine side is important.

Appendix 1:

Meeting agenda

April 10-12, 2017 - Fermilab

https://indico.fnal.gov/conferenceOtherViews.py?view=standard&confId=13692

Monday, April 10, 2017

08:00	Executive Session (30')	Sergei Nagaitsev (FNAL)
08:30	Slides PIP-II Overview: Goals, Status, and Strategy (30')	Stephen Holmes (Fermilab)
Conceptual Design Development (09:00 ->15:00)		
09:00	Slides PIP-II Design Overview (30')	Valeri Lebedev (Fermilab)
09:30	Slides PIP-II Warm Front End (30')	Lionel PROST (Fermilab)
10:00	Discussion (15')	
10:15	Coffee Break (15')	
10:30	Slides Linac Beam Optics and Fault Scenarios (30')	Arun Saini (Fermilab)
11:00	Slides Linac-to-Booster Transfer Line (15')	Alessandro Vivoli (FNAL)
11:15	Slides Electro-dynamical Design of SC Cavities (15')	Paolo Berrutti (Fermilab)
11:30	Slides Mechanical Design of SC Cavities (15')	Ivan Gonin (Fermilab)
11:45	Discussion (15')	
12:00	Lunch (1h0')	
13:00	Cryomodule Design Design of SC Cryomodules (20')	Vincent Roger (FNAL/TD)
13:20	Slides Booster Upgrades (25')	Kiyomi Seiya (Fermilab)
13:45	Slides MI/RR Upgrades (25')	Ioanis Kourbanis (Fermilab)
14:10	Slides Orbit and Optics Measurements and Correction (20')	V.L. S Rao Sista (Bhabha Atomic Research Centre)
14:30	Discussion (15')	
14:45	Coffee Break (15')	
Design Concepts (15:00 ->20:40)		
15:00	Slides RF Sources (20')	David Peterson (Fermilab)
15:20	Slides Superconducting RF: Resonance control (30')	Jeremiah Holzbauer (Fermi National Accelerator Laboratory)
15:50	Slides LLRF (30')	Brian Chase (FNAL)
16:20	Slides Instrumentation (25')	Vic Scarpine (Fermilab)
16:45	Discussion (15')	
17:00	Executive Session (15')	
19:00	Dinner at Chez Leon (1h30')	

Tuesday, April 11, 2017

Design Concepts : (continued) (08:30 ->11:00)

08:30	Slides **RF couplers** (15')	Sergey Kazakov (FNAL)
08:45	Slides **Cryogenics** (20')	Arkadiy Klebaner (Fermilab)
09:05	Slides **Controls** (15')	James Patrick (Fermilab)
09:20	Slides **Radiation Safety** (15')	Paul Derwent (Fermilab)
09:35	Slides **Machine Protection System** (20')	Arden Warner (Fermilab)
09:55	**Discussion** (15')	
10:10	Coffee Break (15')	
10:25	PDF Slides **Conventional Facilities** (20')	Steve Dixon (Fermi National Accelerator Laboratory)
10:45	Slides **Site Power Requirements** (15')	James Steimel (Fermilab)

R & D (11:00 ->12:00)

11:00	Slides **PIP2IT Status and Plans** (20')	Alexander Shemyakin (Fermilab)
11:20	Slides **SRF Research** (25')	Martina Martinello (Fermilab, IIT)
11:45	**Discussion** (10')	

12:00	Lunch (1h0')

Executive Session (13:00 ->18:00)

13:00	**Follow-up questions/discussions as requested by the Committee** (1h0')
14:00	**Executive Session** (4h0')

Wednesday, April 12, 2017

Executive Session and Closeout (08:00 ->13:00)

08:00	**Executive Session** (3h0')
12:00	**Closeout** (1h0')

Appendix 2:

Charge for the PIP-II Machine Advisory Committee (P2MAC)

April 10-12, 2017 - Fermilab

The Proton Improvement Plan-II (PIP-II) represents a significant initial step in upgrading the Fermilab accelerator complex to support a world-leading particle physics research program based on intense beams. The goal of PIP-II is to provide, by the middle of the next decade, 1.2 MW of beam power from the Main Injector for the long baseline neutrino experimental program, while establishing a flexible platform for subsequent development of the accelerator complex. A concept, based on an 800-MeV pulsed superconducting linear accelerator (SCL) to replace the existing 400 MeV linac and accompanied by improvements to the existing Booster, Recycler, and Main Injector, has been documented in a Reference Design Report.

PIP-II is currently in the "project definition" phase, between CD-0 and CD-1. Activities during this phase are centered on conceptual design development, analysis of alternatives, and continuing R&D. The R&D activities are concentrated on the front-end and superconducting cryomodules and their RF systems, and are undertaken in close collaboration with Indian and U.S. national laboratories.

The Analysis of Alternatives report required by DOE O413.3b was prepared and reviewed over the spring/summer of 2016. Based on that report the project has been directed by DOE to proceed with development of a Conceptual Design Report (CDR) based on the alternative described in the Reference Design Report. A complete draft of the Conceptual Design Report is now available.

The P2MAC is asked to review the Conceptual Design Report for PIP-II. In particular we would like specific advice, recommendations, and/or commentary on:
1. Is the scope of the facility described in the CDR both feasible and likely to satisfy the requirements outlined in the Mission Need Statement?

2. Is the facility likely to meet the enumerated performance goals incorporated into the Functional Requirements Specification (FRS).

3. Have the risks inherent in the conceptual design been adequately identified and appropriately targeted within the R&D program?

4. Can the conceptual design be characterized as being sufficient to provide the technical basis for CD-1?

The P2MAC is not limited by these specific charge areas and may delve into other related areas, and offer advice, comment, or recommendations, as it deems appropriate under the general guidance of this charge. We request an oral closeout presentation by the P2MAC with Fermilab and PIP-II management, and DOE observer(s), at the end of the meeting. A written report is requested to be submitted to the Fermilab Chief Accelerator Officer by May 15, 2017.