17 March, 2016

Report from the 4th Meeting of the PIP-II Machine Advisory Committee (P2MAC)

March 15-17, 2016
Fermilab

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1. Introduction

The PIP-II Machine Advisory Committee (P2MAC) held its fourth meeting on March 15-17, 2016, 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. Preparation of the meeting was less efficient than usual, many committee members ignoring where to access information in advance: in the future the link to the web site should be reminded one week before the event.

The Committee is satisfied with the follow-up of its past recommendations and appreciates that they were duly taken into account in a context of restricted resources.

The Committee Charge for this meeting is shown in 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

PIP-II goals, strategy, overall design and status

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). 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, potentially upgradable to CW operation, 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 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. A Joint Project Document for the R&D Phase was signed by DOE and DAE in August 2015.
For the linac, the PXIE test set-up is an essential part aimed at testing/demonstrating the low energy front end, the HWR section and the first set of SSR1 cavities in a cryomodule. 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 tested.
For the existing rings, simulation and beam tests have to be combined to give confidence in the feasibility of the expected performance goals. Hardware replacement (RF cavities in the booster and Recycler), upgrade (RF in the Main Injector) or additions have to be prepared (gamma-t jump in the booster, collimators in the Recycler…).

Technical progress has been good in 2015, with the following main achievements:

- Two SSR1 cavities have been received from IUAC and successfully processed/tested at Fermilab,
- The RFQ has been delivered by LBNL in September and successfully conditioned at nominal RF power early in 2016,
- The LEBT has been commissioned in PXIE.

The PIP-II Reference Design Report was released in May 2015, as a key contribution to the DOE independent review of PIP-II which took place in June. It concluded stating that "The proposed concept is well-advanced, beyond what is required at this stage…most likely will satisfy the P5 recommendation".
CD-0 was granted in November.
The next goal is CD-1, tentatively expected during FY2017. The main deliverable is a Conceptual Design report, with analysis of alternatives. The evaluation criteria which remain to be finalized will clearly be crucial to the outcome of the process.

Comment

- The Committee congratulates all contributors, in the USA and in India, for the good progress in 2015, on the technical as well as on the management fronts.
- The Committee takes note that the upgrade of the rings is now an integral part of the PIP-II work program.
- However it is worrying to observe that more subjects should be addressed during the present phase than what resources permit (e.g. design of the booster injection girder, construction of the collimators in the recycler, early test of power amplifiers, etc.) and that some activities are delayed (e.g. SSR1 CM, resonance control). Risks during the construction are hence likely to remain significant.

Q1: Conceptual Design Development:

a) Are the plans for developing the PIP-II conceptual design, with the Reference Design as a starting point, likely to yield a design meeting the enumerated performance goals?

The plans for preparing PIP-II linac construction phase are well-motivated and cover essential subjects for the linac to reach the required beam characteristic. However, the efforts required for demonstrating that the existing machines can reach the required performance shall not be underestimated. Pace of progress for the Booster, Recycler and Main Injector is slow because of resources limitations (e.g. design of the booster injection girder, construction of the collimators in the recycler, early test of power amplifiers, etc.).

b) What alternatives to the approach outlined in the Reference Design might be considered?

The main alternative to the proposed version of PIP-II is to limit the future linac to pulsed operation. Renouncing to CW would bring-in significant benefits during construction and exploitation: heat dissipation in the amplifiers would be much lower, reducing construction and maintenance cost, electrical consumption would be drastically lower (cryogenics, RF, magnets), chopping would be simpler… If the instantaneous beam current is increased, resonance control becomes less challenging and the duration of injection in the booster can be reduced. If interesting for physics users, a higher pulsing rate could also be considered as an upgrade.

Q2: R&D Program:

a) Is the R&D plan properly directed at addressing the primary technical and cost risks in an effective manner?

YES.
The R&D plan covers all critical items, but the rate of funding is a clear limitation that necessitates prioritization. The potential need for CW operation in the long term complicates today's R&D program and is a drain of resources (e.g. for amplifiers, chopper...).

b) Are the risks appropriately prioritized and will the completion of the R&D plan provide a basis for proceeding to the construction phase with confidence that performance goals can be met?

Prioritization is not fully clear to the Committee.

Some R&D tasks clearly deserve more attention, e.g.:

- For the linac, resonance control is a crucial subject which benefits from LCLS-II developments but still deserves additional efforts for PIP-II. Allocating more time for testing with cold cavities is highly recommended.
- For the rings, the design of the injection girder in the booster is a difficult issue which deserves being addressed as soon as possible. This is also the case of the construction of the collimators for the Recycler which is necessary to reach the PIP goal of 700 kW beam power, but is also a mandatory step towards demonstrating the potential of the Recycler to attain PIP-II performance goals.

c) Is the R&D program proceeding satisfactorily toward a construction start near the end of the current decade?

At the current level of financing it is not obvious that the R&D program will converge on time to minimize risks.

Many items in the PIP-II R&D are on the critical path for starting construction in 2019 (e.g. PXIE). The SRF R&D and prototyping efforts are well past CD-0 in many areas but, due to various reasons, some delays are noticed wrt plans presented during the previous PIP-II MAC.

Q3: India Collaboration:
Is the program, and division of responsibilities, outlined in the Joint R&D Project document well aligned with the needs of PIP-II, and will it support a construction start encompassing both U.S. and Indian deliverables?

The Indian partners have an important role in the Joint R&D project which depends critically on their contributions being delivered on time and meeting specifications. The same will be true during the construction phase. The Committee is confident in the will and competence of the Indian laboratories, but considers that their contributions should be monitored and reviewed like those from other partners. That will be even more important during the construction phase, where similar project management and system engineering practice have to be applied throughout the project (Progress report, Quality Assurance, Engineering documentation validation and storage…).

Recommendations

R1: Investigate/estimate the uncontrolled variations of the linac beam energy.
Implementation of an additional system for energy stabilization during the pulse should only be considered as a last resort corrective measure.

R2: For the alternative solution of an sc linac operating only in pulsed mode, optimize the pulse current and pulse structure.
Renouncing to CW would bring-in significant benefits during construction and exploitation: heat dissipation in the amplifiers would be much lower, reducing construction and maintenance cost, electrical consumption would be drastically lower (cryogenics, RF, magnets), chopping would be simpler… If the instantaneous beam current is increased, resonance control becomes less challenging and the duration of injection in the booster can be reduced. If interesting for physics users, a higher pulsing rate could also be considered as an upgrade.

R3: Prioritize the design of the Booster injection girder and the whole injection scheme to demonstrate the feasibility of the long injection time needed with a 2mA linac beam.

R4: Pursue simulation and code development for RF gymnastics in the rings in collaboration with other laboratories.

R5: Continue to address the identified R&D areas but further prioritize in case of resource challenges.
One possibility would be to decrease the priority given to the CW requirements.

R6: Identify the risk of single source dependencies and develop mitigation plans where appropriate.

R7: Project management and system engineering practice have to be standardized throughout the PIP-II project (Progress report, Quality Assurance, Engineering documentation validation and storage…). All contributions should be monitored in a similar fashion by the various review and advisory committees.

R8: Resonance control of the SRF cavities is a crucial subject which deserves additional efforts. Allocating more time for testing with cold cavities is highly recommended.

R9: For the solid state amplifiers, place order early to reach nominal performance in time.
Don't underestimate the amount of spares parts necessary to commission and maintain operational equipment. **The Committee remarks that most troubles encountered are linked to CW operation of the amplifiers.**

3. Complementary observations and reactions

Linac

Answers to last year's recommendations:

L1: *Specify "particle free" conditions for the last part of the MEBT.*

First estimates of the "particle free" length have been made using the closing time of the fast vacuum valves in front of the first SC module. So far, a length of ~5 m is considered. The answer is satisfactory.

L2: *Consider measures to reduce the filling/decay times in the cavities for pulsed operations.*

A first analysis was made and is reported in the RDR. The issue will be re-considered for the CDR. The answer is satisfactory.

L4: *Translate the needs for mechanical stability of cavities and cryomodules into functional specifications for the civil engineering design (if needed).*

Functional specifications are being prepared for FESS, which is then expected to take measures to reduce vibrations in critical areas. The issue is not yet solved, but progress has been made.

Findings:

The linac architecture has not changed since the last MAC meeting and with the project having passed the CD-0 milestone it is likely that this layout will be kept. The conceptual design report is expected for July 2016. The base line design foresees initial operation in pulsed mode (20 Hz, 0.55 ms, 2 mA) before moving to CW operation in the future. The design of the cryo-modules and the cavity tuning systems profits from the requirement of operating in CW and in pulsed mode. This results in a very robust design, which will be beneficial even in the case, where the machine would operate only in one of these modes.

As part of the CD-1 requirements, 3 alternative solutions to the base line have to be explored and evaluated. The PIP-II project management has suggested evaluation criteria to the DOE.

The end of the design phase is foreseen for 2019 and start of operations is planned for 2026, which is well in line with the LCLS-II planning. PXIE, which is meant to verify the main technical choices and the operation of RFQ, MEBT, HWR, SSR1, is planned to be operational in 2018, just in time for the transition from design to construction phase.

The Indian contribution to PIP-II construction is of the order of 200 M$ (Value of the contribution if it was done at FNAL) and was taken into account when the total construction cost of the project was estimated to be between 450 M$ and 650 M$.

Perceived Challenges:

a) Defending the base-line scenario against the 3 alternative solutions, which may be cheaper but have less physics reach in the future.
b) An R&D program has been established to address the major technical challenges, mostly within PXIE. However, the execution seems to be slowed down by lack of funding and even if PXIE is operational on time, it will be late for benefiting from the whole experience it will bring.
c) The highest risk for cost and schedule is the SRF system (cavities, cryomodules, RF system), which accounts for 50% of the total project cost.

d) Longitudinal energy stability of 10^{-4} at the linac output is needed for injection into the Booster. A scenario has been defined, which uses the first 100 μs of each pulse to stabilize the linac energy via a feedback system using the last SRF cavity.
e) The design needs to aim at extremely high reliability since the failure of s.c. cavities can only be accepted at the high energy end of the linac.

Proposed Solutions:

a) Define clearly the physics reach of each alternative design and compare the physics options with ongoing or planned programs at other labs.
b) Prioritize the R&D topics, e.g. the work on CW-specific issues (e.g. solid state amplifiers or beam chopping) could be slowed down, while work on fast tuners needs to proceed.
c) Make sure that the SRF development is done in close collaboration with the Indian partners but - at the same time - develop a back-up procurement strategy for cavities, cryo-modules, ancillaries and RF sources. It is understood that this mitigation approach is already partly being followed.
d) Before defining a strategy how to decrease the energy jitter of the linac beam it should be assessed how much energy jitter is expected from the linac and whether it can be reduced by revising certain RF specifications (e.g. phase and amplitude stability in the low-frequency part) or by revising some layout aspects.

Comments:

If the need to reduce energy jitter is confirmed, different options should be considered. The proposed stabilization scheme based on the removal of 100 μs out of each pulse should be compared to other possibilities like e.g. the use of a normal conducting buncher cavity in the transfer line (NC technology would remove the need to have a SC infrastructure at the location of the cavity).

Linac design Recommendations:

R1: Investigate/estimate the uncontrolled variations of the linac beam energy and then assess options to decrease it.
Implementation of an additional system for energy stabilization during the pulse should only be considered as a last resort corrective measure.

R2: For the alternative solution of an sc linac operating only in pulsed mode, optimize the pulse current and pulse structure.
Renouncing to CW would bring-in significant benefits during construction and exploitation: heat dissipation in the amplifiers would be much lower, reducing construction and maintenance cost, electrical consumption would be drastically lower (cryogenics, RF, magnets), chopping would be simpler… If the instantaneous beam current is increased, resonance control becomes less challenging and the duration of injection in the booster can be reduced. If interesting for physics users, a higher pulsing rate could also be considered as an upgrade.

Rings

Findings:

The Booster has successfully demonstrated full 15Hz operation. To reach the desired 160kW at 8GeV, while the linac output current is 2mA, it is proposed to (1) raise the beam pulse repetition rate to 20Hz from 15Hz, and (2) increase the injection time to 0.55ms. 20Hz magnet ramping has been studied and shown to be technically feasible.

The linac is situated to require a new injection point L11 rather than L1. The new injection girder is yet to be designed, but it is known that to create sufficient space, the 2 adjacent combined function dipoles will have to be shortened.

A program of experiments and simulations to verify low loss transition crossing have been performed and are continuing. A new code is being developed.

To mitigate reliability issues with the existing RF cavities in the Booster, new cavities with perpendicularly-biased ferrites are being designed and tested. In addition to being more reliable they would also have possibly as much as 4 times more voltage per unit cavity length.

The code SYNERGIA is being used to simulate slip-stacking in the recycler ring.

The design for a Recycler collimation system has been finalized and is to be installed during the next two summer shutdowns. Each of the 4 secondary collimators is designed to handle up to 2 kW of beam loss.

Comments:

The Recommendations made in the 2015 report have been followed up: beam dynamics studies to identify performance-limiting mechanisms have been initiated, Booster transition-crossing has been studied, code development is in progress.

The feasibility of 2mA linac injecting into the Booster to obtain 160 kW depends crucially upon the injection scheme and in particular upon a long, 0.55 ms injection time. The design of the injection girder and the concept of extending injection time to 0.55 ms required have yet to be done.

Doubling the Booster injection energy is key to mitigating the space charge effects. In addition, simulations indicated that sensitivity to the space charge would be greatly reduced if Booster lattice were periodic. However, the modification of L11 to allow 800 MeV injection will work against this in making the lattice less periodic and thus increasing the strengths of betatron resonances.

Space charge study is usually combined with analysis of linear (coupling) and nonlinear resonance excitation and compensation with correctors. Such studies are extensively performed on other machines like BNL AGS/RHIC, CERN, and J-PARC. We encourage the PIP II team to reach out and deepen the understanding of space charge and lattice perturbation mechanisms.

The possibility of developing Booster RF cavities with twice higher cavity voltage occupying half the space is very exciting; the committee encourages continued work in this direction.

Transition crossing in general is a mature area well studied for many machines with adequate theoretical understanding and experimental verification, including the chromatic nonlinear effects, space charge and longitudinal impedance induced bunch mismatch, negative mass instability due to space charge and microwave instability due to broadband impedance, and electron cloud effects. Compensation methods are also well studied and documented.

Slip-stacking in the RR simulation studies are continuing, but in our judgement the simulations are not of sufficient number of turns to demonstrate convincingly that losses will be below 3% as required. We encourage extra studies and code development as well as obtaining extra computing power for these studies. The collimation scheme to localize losses does look promising.

Electron cloud effect can be another performance limiting mechanism to the PIP II rings. The project team is collaborating with KEK on simulations. A PhD student is also working on the subject. We encourage the project team to intensify the study with the goal of reaching a conclusion on needed hardware improvements possibly including beam scrubbing and vacuum chamber coating.

Recommendation:

R3: Prioritize the design of the Booster injection girder and the whole injection scheme to demonstrate the feasibility of the long injection time needed with a 2mA linac beam.

R4: Pursue simulation and code development for RF gymnastics in the rings in collaboration with other laboratories.

CF

Findings

The linac site was optimized considering following factors;

- Accommodate Future Linac Extension,
- Accommodate Future Beamline to Muon Campus,
- Transport Line Crosses Above Main Ring (8'-0" clear),
- Investigate Depth of Linac.

The linac site has changed and now linac gallery/linac service building are in between linac and main building, beam dump has moved after 1st arc to provide extension of linac for future upgrade and provided beam energy diagnostic. Cooling water strategy has been developed for linac and transfer line. Through linac elevation is same as booster and main ring, transport line crosses above main ring (8'). New siting also accommodates future beam line to Muon campus. New siting also minimizes the impact on wetlands. Planned activities have started toward CD-1.

Comments

The proposed layout is based on the standard construction practice. Further optimizations and/or justifications have to be taken into account: the CF team has to work closely with technical groups to refine location and elevations of tunnels and building requirements. Some critical facilities such as the cryogenic plant and cryo-transfer lines need to be considered for the site optimization.

Engineering activities

Answers to last year's recommendations

(R8) The Committee is convinced of the importance of System Engineering and Integration and strongly encourages a proper implementation. Early agreement on this practice with partner laboratories will be essential for the in-kind contributions from international partners

The Committee is pleased to see response that Teamcenter and SharePoint are being increasingly adopted.

Findings

PIP-II engineering document management is now using Teamcenter (Item # ED00011224). Many Functional and Technical requirement specification has been written via Teamcenter EPDMs which is directly accessible by collaborators. Budget and scheduling documents has been implemented via Teamcenter in support of project financial requirements. The IIFC collaborators are fully integrated and utilize SharePoint and Teamcenter daily to work as a unified team.

Comments

The Committee encourages that more people are trained to use Teamcenter and SharePoint.

Transfer Line

Findings

The transport line to the booster was redesigned to accommodate a switchyard between two arcs. The switchyard consists of fast kicker and septum magnets for switching beam between three destinations: beam dump, booster and Mu2e campus. Rolling dipoles in the 2nd arc deflect the beam vertically and make the transport line cross the main ring at 8 feet above the existing beam line. The dump line is proposed to be used as part of linac energy stabilization system. Beam energy is measured by time-of-flight system in energy upgrade slots and by BPMs in the arcs, and it is modified by voltage correction in the cavities of the last super conducting cryomodule. After 100 μs the energy is stabilized and the beam is switched to the Booster. To minimize beam loss the switching time must be of the order of 20 μs.

Comments

No R&D is foreseen for the elements of the transport line. Rolling dipoles generally couple horizontal and vertical planes. This coupling must be investigated. Energy stabilization could also be achieved with a buncher cavity in the transport line. It could be a normal conducting cavity.

R&D

Findings

The PIP-II R&D program is defined with the goal to mitigate technical and cost risks by validating the choices made in the PIP-II facility design and by establishing fabrication methods for major subsystems and components. The qualification of possible suppliers is included also. In general technical risks are to be eliminated or at least to be minimized. It is understood that remaining technical risks will create the need for increased contingency. In general, the current R&D plan is foreseen to support the currently understood project cost and the set schedule goals.

The scope of the PIP-II R&D program is to study the following general issues with the goal to be ready for CD-3 (approve start of construction) in 2019:

- An 800 MeV superconducting linac, constructed of CW capable accelerating structures and cryomodules, initially operating with a peak current of 2 mA and a beam duty factor of 1%,
- Beam transport from the end of the SCL to the new Booster injection point, and to a new 800 MeV dump,
- Upgrades to the Booster to accommodate 800 MeV injection, and acceleration of 6.4×1012 protons per pulse,
- Upgrades to the Recycler to accommodate slip-stacking of 7.7×1013 protons delivered over twelve Booster batches,
- Upgrades to the Main Injector to accommodate acceleration of 7.5×1013 protons per pulse to 120 GeV with a 1.2 second cycle time, and to 60 GeV with a 0.8 second cycle time.

Primary areas to address technical risk were presented in an overview presentation, followed by detailed presentations on individual R&D topics. The explicitly named areas for R&D are:

- the development and integrated systems testing of PIP-II Front End components (PXIE)
- the development and demonstration of cost effective superconducting radio frequency acceleration systems at three different frequencies and with rf duty factors ranging from 10% to 100%
- the development of requisite capabilities at international partner institutions to successfully contribute to PIP-II construction
- the development of a Booster injection system design capable of accepting extended beam pulses from the PIP-II linac
- the development of designs capable of supporting a 50% increase in the proton beam intensity from the Booster/Recycler/Main Injector complex

The overall schedule for the presented R&D activities was summarized and collaboration partners were named. The PXIE schedule and the schedule for the SRF part of the PIP-II development phase were given. The joint Fermilab / India activities were emphasized.

The good progress at PXIE should allow for a first beam through the RFQ during FY16. The carefully defined R&D deliverables aim for building strong collaborations with Indian Institutions. The R&D on rings has been delayed because of funding constraints. Work on SSR2 and high beta 650 MHz cavities is de-emphasized.

Observations

The P2MAC was asked if the R&D plan is properly directed at addressing the primary technical and cost risks in an effective manner.

- The R&D plan is absolutely valid since all major technical risks are principally addressed. But due to underfunding prioritization may be needed. Not all areas can be worked on in parallel.
- The highest cost risk is clearly with the different SRF cavities and systems. Emphasizing the respective development is clearly an appropriate prioritization.
- Any R&D goal not reached will require increased contingency due to higher risk during the project realization phase.

The P2MAC was asked if the risks are appropriately prioritized and if the completion of the R&D plan will provide a basis for proceeding to the construction phase with confidence that performance goals can be met.

- The joint R&D efforts with especially Indian institutes but also ANL, LBNL and others are of utmost importance. Nevertheless, it should be clearly understood which single source dependencies remain and are seen critical. All technically demanding systems which require development of infrastructure and esp. industry need a back-up solution.
- The development of new electronic circuits, be it solid state RF amplifiers or LLRF control boards, needs to take care of long-standing availability of the used components. Collaboration with other developers in the community is appreciated. Common standards can help to develop the market.

Further on the P2MAC was asked if the R&D program is proceeding satisfactorily toward a construction start near the end of the current decade.

- The presented schedules are clearly success oriented with only little time for iteration.
- The actually available funding may directly impact the work towards CD-1. CD-2 (approval of the performance baseline) will give a more solid agreement and allow for a better matched funding profile.
- Some task leaders mention resource challenges due to other obligations. The LCLS-II activities and the obligations related to the ongoing accelerator operation may impact the pace of PIP-II R&D. New infrastructure like the Lab2 cleanroom is very much appreciated.

Recommendations

R5: Continue to address the identified R&D areas but further prioritize in case of resource challenges.
One possibility would be to decrease the priority given to the CW requirements.

R6: Identify the risk of single source dependencies and develop mitigation plans where appropriate.

International Collaboration

Findings

The PIP-II R&D program is strongly and visibly based on international collaboration with several Indian institutes namely Bhabha Atomic Research Center (BARC), Mumbai, Inter-University Accelerator Center (IUAC), New Delhi, Raja Rammana Center for Advanced Technology (RRCAT), Indore, and Variable Energy Cyclotron Center (VECC), Kolkata.

The DOE-DAE Collaboration aims for two-way support of high intensity accelerator projects in the U.S. and in India. In India, both RRCAT and BARC are aiming for >MW proton linacs which have strong similarities with the 800 MeV PIP-II design. Thus the collaboration specifically targets collaborative R&D on superconducting radio frequency technologies as applied to high intensity proton linear accelerators. The scope of work includes development of the accelerator physics design for the linac, of cavities and cryogenic accelerator modules at various frequencies, infrastructure related to sc accelerator sections, rf power sources, instrumentation, controls and cryogenics.

The foreseen Indian contribution to the PIP-II realization is enormous. Approx. 25% of the total project cost, and may be an even larger fraction of the accelerator cost are expected. Thus the success of the started common R&D program is of utmost importance.

The character of work in all respective areas as joint activity was stressed repeatedly. Fermilab is responsible for the general design and the specifications. The Indian partners take care of the detailed design including fabrication drawings. The goal is to produce the resulting accelerator components at Indian companies.

Part of the work done by Indian engineers is carried out at Fermilab. Thus a direct supervision by Fermilab experts seems possible. Regular weekly video meetings take place, quarterly meetings in India are planned, but also the direct exchange of status and results shared via a common EDM system guarantee communication.

Many examples of common development were given:

- MEBT Magnets
- 325 MHz RF sources
- LLRF / RF protection interlock
- 2 SSR1 cavities
- SSR2 Cavity Design
- LB650 Cavity Design
- HB650 End Group, He Vessel, Tuner
- 650 Cryomodule Design
- SSR2, LB650 cavities for power test
- HB650 cavities for CM test
- 650 MHz Horizontal Test Stand design, fabrication, commissioning

There is quite some progress in all areas. First components are delivered, in some cases iterated. Design work is carried out as collaborative effort.

Observations

The PIP-II R&D plan is strongly based on the success of collaboration with institutes from India. The so far gained experience is obviously used to further detail the work break down in different fields. Emphasizing the joint work is promising but success is also a must.

The shared work should lead into shared intellectual property. The P2MAC assumes that the presented documentation in the Fermilab EDM system gives the PIP-II project management the full knowledge of all details. At the same time the exchange of designs, drawings, specifications etc. should be limited to the project activities. The obvious definition of different roles for EDMS users is appreciated since the aggressively promoted technology transfer has to take care of possible vendor interests. Fermilab involvement in other major projects should also not lead to conflicts of interest. Confidentiality has to be respected wherever assured.

The incorporation of a really large contribution to both, the PIP-II R&D and later to PIP-II is very desirable. But it doesn't come without risk. The successful technology transfer requires a remarkable coordination effort. Even if successful, the schedule risk could be immense. Fermilab as project leader has the coordinator role, and thus has to be prepared to mitigate all major risks.

The careful set-up of project management plans is appreciated. Due to the quite demanding technology detailed Quality Management Plans should be established. The supervision of in-kind contributions can become a challenge. Fermilab should be prepared for regular visits at partner institutes and international companies.

The possible in-kind contribution of Indian institutes to the PIP-II realization requires mutual understanding of the incitement to guarantee schedules. The sophisticated supply chain of sub-components of superconducting accelerator modules require a more than strong collaboration. All partners need an incentive and technology transfer may not be sufficient.

Fermilab and DOE are also working to develop collaborative programs with UK, France and Italy. The in-kind contributions of STFC/UK, Saclay in France, and INFN Milano in Italy to the European Spallation Source are an excellent reason to search for further collaboration.

Recommendations

R7: Project management and system engineering practice have to be standardized throughout the PIP-II project (Progress report, Quality Assurance, Engineering documentation validation and storage…). All contributions should be monitored in a similar fashion by the various review and advisory committees.

PXIE and RFQ

Status and Findings

PXIE aims at development and integrated system testing of PIP-II Front End components. Its purpose is to mitigate most risks related to the frontend. The main parameters are unchanged since the last P2MAC.

- *Ion source*

The ion source (IS) has been operated up to 10 mA in DC and pulsed modes. A low uncontrolled beam loss beyond the IS vacuum chamber exit aperture was found and reduction efforts have been made.

Uninterrupted operation of > 48 hours and average filament lifetime > 300 hours (maximum up to 800 hours) have been demonstrated.

The LEBT has been commissioned with the exception of the bending dipole magnet which has yet to be installed.

A scraper which has a small size, a regular size and D-shaped apertures, has been installed, to trim the beam entering the RFQ. This is also used as a beam current monitor and a tool of the Machine Protection System.

Comparison between the measurements and simulations indicate a 70-80% space charge neutralization upstream of the chopper.

- *RFQ*

The RFQ was delivered from the LBNL in September 2015 and installed at the PXIE site.

The bead pull measurement shows that the average field flatness of 2% was achieved. Some other low level RF measurements, such as coupling and higher order modes, were done. The frequencies of the higher order modes are consistent with the simulation results.

The flatness of the average field of the RFQ is good, but there is a 1mm horizontal bow in the RFQ vanes. This so far has no apparent detrimental effect on its performance.

The RFQ was successfully conditioned with 120 kW input power and 5% duty cycle. The X-ray spectra were measured in the RFQ vacuum chamber to obtain intervane voltage. It showed a shut impedance of 19 kOhm, which is within 10% of calculated impedance.

A failure of the amplifier occurred during CW operation. Spare components will be delivered by May 2016, but the failure mode is not yet understood.

Preparation for RFQ beam commissioning is underway. The first pulsed beam is expected in April.

- *MEBT*

The MEBT consists of 25 quadrupoles and three bunching cavities. 4 quadrupoles have been delivered from BARC, and are within spec.

A prototype of the bunching cavity was fully tested.

The chopper system with two kickers and absorbers, is designed to be capable of bunch-by-bunch selection. 4 scraper sets will be used to scrape the beam halo, for diagnostics, and also form part of the MPS. One set was successfully tested at LEBT.

Two traveling-wave kickers and absorbers will be used. The absorber accepts 21 kW of CW beam. Two versions of kickers, 50 Ohm and 20 Ohm have been developed and tested.

Vacuum components and pressure are analyzed. The main purpose is to keep the area particle-free in the last ~3m. The design of the differential pumping section has started.

Staged beam commissioning plans are synchronized with the magnet delivery schedule. The initial configuration has been set and is awaiting the RFQ beam. The final MEBT will be FY18 which consists of particle-free vacuum chamber and final chopping system.

Comments

The committee appreciates the good progress of the commissioning of ion source, LEBT, RFQ and MEBT. The beam commissioning strategies of the RFQ and the MEBT are well planned.

The Twiss parameters of the ion source beam have shown slow drifts over periods of hours to days. The reason is not yet clear. This may be due to temperature effects or slowly conditioning surfaces resulting in varying space charge neutralization.

Space charge neutralization time constant is a few 10's of microseconds. This may interfere later with plans for fast piezo tuning of the SRF cavities. It can be manipulated to some extent with clearing electrodes and vacuum pressure.

The committee has a concern that the failure of the power supply for the RFQ is not yet understood.

The staged commissioning of the MEBT and RFQ, seems sound and reasonable.

SRF

Findings and comments

The superconducting linac portion of the PIP-II consists of five types of SRF cavities (HWR, two SSR and two elliptical) operating at three different frequencies (162.5 MHz, 325 MHz and 650 MHz). In total 126 SRF cavities will be housed in 25 cryomodules.

Systems and subcomponents are being designed and prototyped for CW operation as well as for pulsed operation. It is reported that a full size cryogenic plant (2.5-3 kW at 2K) for CW operation is also being considered as a baseline for PIP-II. As PIP-II operation will be in pulsed mode for a while, balancing the plant with load should be carefully analyzed and reflected into the design including large turn-down capability.

There has been a question about inadequacy between RF duty factor, cryogenic dynamic load, beam current, and beam duty, which weakens the justification to use superconducting accelerating structures for the proposed pulsed operation.

A solid team has been assembled. The SRF R&D and prototyping efforts are well past CD-0 in many areas but, due to various reasons, some delays are noticed with respect to plans presented during the previous PIP-II MAC.

Cryogenic load at 2K is estimated to be 2.2 kW for CW operation with design Q_0 specifications. Results from cavity testing to date for HWR, SSR1 and elliptical cavities have far exceeded the design specifications.

R&D scopes and deliverables are well defined.

- Test of one cryomodule at each frequency (HWR, SSR1, HB650). HWR and SSR1 cryomodules will be tested with beam within the PXIE R&D scope. HB650 prototype cryomodule will be tested in a standalone mode.
- Resonance control in pulsed mode operation.
- Test of two SSR2 dressed cavities and two LB650 cavities.

ANL is responsible for the HWR cryomodule development. Fabrication of production cavities is completed. The first production cavity with the superconducting solenoid is tested with successful results. No measurable changes are observed on Qo from the stray magnetic field. Another six production cavities are in various stages and will be tested in near future before installation. Preparation of subcomponents (coupler, tuner, BPM) is progressing, aimed at cryomodule commissioning with beam in FY18.

SSR1 cryomodule development is underway for the commissioning with beam in FY18 as well. The commissioning of SSR1 cryomodule will be in both CW and pulse modes. The first jacketed SSR1 cavity is successfully tested, fully integrated with a prototype tuner and a prototype coupler. Two SSR1 cavities will be provided by the Indian partner. A few schedule issues are identified for SSR1 cryomodule completion such as coupler delivery, IIFC SSR1 cavity delivery and the new assembly facility timing. SSR2 cavity and cryomodule design will be based on the experiences and lesson learned from SSR1 cryomodule. RF design of SSR2 cavity is finished and multipacting is much reduced through careful analysis.

The prototype high beta cryomodule (HB650 pCM) is being developed jointly between FNAL and RRCAT. The work scope for each party is roughly divided. The commissioning of the

HB650 pCM is scheduled at the end of 2019. A strong focus on this effort will be needed to meet the schedule.

The bandwidth of PIP-II cavities is narrow (~30 Hz) due to low beam loading. The allowable detuning is 20 Hz based on the RF power budget. Successful compensation of cavity vibration, especially Lorentz Force detuning in pulsed mode operation, is the most critical aspect for the operability. A reliable and robust fast tuning mechanism is crucial for reliability and availability of the linac. This requires integrated engineering efforts and test of whole resonance control system at similar operating conditions to be successful.

Recommendation

R2: For the alternative solution of an sc linac operating only in pulsed mode, optimize the pulse current and pulse structure.

Renouncing to CW would bring-in significant benefits during construction and exploitation: heat dissipation in the amplifiers would be much lower, reducing construction and maintenance cost, electrical consumption would be drastically lower (cryogenics, RF, magnets), chopping would be simpler… If the instantaneous beam current is increased, resonance control becomes less challenging and the duration of injection in the booster can be reduced. If interesting for physics users, a higher pulsing rate could also be considered as an upgrade.

R8: Resonance control of the SRF cavities is a crucial subject which deserves additional efforts. Allocating more time for testing with cold cavities is highly recommended.

RF and Beam Instrumentation

Answers to last year's recommendations:

L2: *Evaluate the risk related to the single window RF power coupler design of SSR1.*
The couplers are tested at much higher power than needed for operation. Also the design of double window couplers is studied as a possible alternative. The answer is satisfactory.

R9: *Develop a project-wide strategy to identify a passive measure supporting a successful resonance control.*
Passive measures to support cavity resonance control are being included in the functional requirements specifications and the RF peak power is being increased as a means to compensate in case other measures are not effective. We acknowledge that measures are taken and look forward to their successful implementation.

Findings:

The development of solid state RF amplifiers, RF interlock systems, LLRF and Controls is done in close collaboration with the Indian partner labs. Test stands and R&D programs have been defined for all critical components and the document management system is developed such that it can be used by all collaborators worldwide. Technical specifications and quality assurance procedures are developed with the partner labs as part of the collaboration.
There is a well-defined R&D program for diagnostics and PXIE will serve as a test bed for debugging these systems.

Perceived Challenges:

a) Resonance control of SC cavities in pulsed mode: The functioning of the fast tuners is mandatory for pulsed operation.
b) Interfacing of RF amplifiers with controls, interlocks, and LLRF.
c) Reliable operation of solid state amplifiers.

Proposed Solutions:

a) Prioritize the work on fast tuners and the associated controls, which may need long test campaigns in order to verify reliability.
b) Integration test stands are being established to test and develop the interfaces. This seems adequate.
    i) Horizontal dressed cavity test stand for 650 MHz. Operational in 2017.
    ii) SSR1 CM with RF power and beam, expected for the end of 2018.
    iii) Integrated test of HB650 cryomodule with RF power foreseen for the end of 2018
c) Proceed with the procurement of spare parts and the debugging of the existing faulty systems. Proceed with the specification and integration of the LLRF and Controls interfaces of the Indian amplifiers.

Comments:

Without functioning fast tuners, pulsed operation of the PIP-II linac will not be possible. Prioritization of this R&D activity and testing at cold under operational conditions is obligatory (see recommendation in the SRF section).

The development of solid state amplifiers for all cavities is progressing with several teething problems. Many of these problems are linked to CW operation and would become easier if the requirement for CW operation is abandoned. For the higher power systems of the 650 MHz section, alternative solutions would be worth investigating. IOTs are likely to be more efficient both in terms of cost and energy. Another option is to pursue the R&D on magnetrons, which showed promising results on low-power prototypes.

First tests of solid state amplifiers in CW showed a lot of faults and required many spare parts, which often have long order times.

The R&D effort on LLRF and diagnostics systems is felt adequate.

RF system Recommendations:

R9: For the solid state amplifiers, place order early to reach nominal performance in time. Don't underestimate the amount of spares parts necessary to commission and maintain operational equipment. **The Committee remarks that most troubles encountered are linked to CW operation of the amplifiers.**

Appendix 1:

Meeting Agenda

https://indico.fnal.gov/conferenceDisplay.py?ovw=True&confId=11396

Tuesday 15 March 2016

08:00	00:30	08:30	S. Nagaitsev	*Executive Session*
08:30	00:30	09:00	S. Holmes	PIP-II Overview: Goals, Status, and Strategy
Conceptual Design Development				
09:00	00:30	09:30	V. Lebedev	PIP-II Design Overview
09:30	00:30	10:00	F. Garcia	800 MeV Linac
10:00	00:15	10:15		*Discussion*
10:15	00:15	10:30		*Coffee Break*
10:30	00:20	10:50	A. Vivoli	Transfer Line
10:50	00:25	11:15	B. Pellico	Booster Upgrades
11:15	00:30	11:45	I. Kourbanis	MI/RR Upgrades
11:45	00:15	12:00		*Discussion*
12:00	01:00	13:00		*Lunch*
13:00	01:00	14:00	L. Ristori, J. Leibfritz	*Tour*
14:00	00:25	14:25	S. Dixon	Siting/Conventional Facilities
14:25	00:15	14:40	D. Mitchell	Engineering Activities
R&D Program				
14:40	00:25	15:05	P. Derwent	R&D Program Overview
15:05	00:15	15:20		*Discussion*
15:20	00:15	15:35		*Coffee Break*
15:35	00:20	15:55	L. Prost	PXIE Ion Source and LEBT
15:55	00:25	16:20	J. Steimel	RFQ Status and Commissioning Plan
16:20	00:25	16:45	S. Shemyakin	MEBT Status and Commissioning Plan
16:45	00:15	17:00		*Discussion*
17:00	01:30	18:30		*Executive Session*
19:00	01:30	20:30		*Dinner*

Wednesday 16 March 2016

08:30	00:30	09:00	S. Mishra	International Collaborations
R&D Program (cont)				
09:00	00:15	09:15	A. Rowe	Superconducting RF: Strategy and Organization
09:15	00:20	09:35	P. Ostroumov	Superconducting RF: HWR Status
09:35	00:30	10:05	L. Ristori	Superconducting RF: SSR1, SSR2 Status
10:05	00:20	10:25	T. Nicol	Superconducting RF: LB650, HB650 Status
10:25	00:15	10:40		*Discussion*
10:40	00:15	10:55		*Coffee Break*
10:55	00:20	11:15	W. Schappert	Superconducting RF: Resonance control
11:15	00:20	11:35	B. Chase	LLRF
11:15	00:15	11:30	R. Pasquinelli	RF Sources
11:35	00:15	11:50	V. Scarpine	Instrumentation
11:50	00:10	12:00		*Discussion*
12:00	01:00	13:00		*Lunch*
Executive Session				
13:00	01:00	14:00		Followup questions/discussions as requested by the Co
14:00	03:30	17:30		Executive Session

Thursday 17 March 2016

08:00	03:00	11:00		Executive Session
11:00	01:00	12:00		Closeout
12:00				Adjourn

Appendix 2:

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

March 15-17, 2016 - 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 has received CD-0 from the Department of Energy and is now formally in the "project definition" phase. Activities during this phase are centered on conceptual design development, evaluation of alternatives, and continuing R&D. 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 P2MAC is asked to review the plans for PIP-II including R&D activities and development of the conceptual design. Advice and/or recommendations are sought relative to the challenges of the current design concept, the evaluation of alternatives, and the appropriateness of the accompanying R&D program. In particular we would like specific advice, recommendations, and/or commentary on:

1. **Conceptual Design Development:** a) Are the plans for developing the PIP-II conceptual design, with the Reference Design as a starting point, likely to yield a design meeting the enumerated performance goals? b) What alternatives to the approach outlined in the Reference Design might be considered?

2. **R&D Program:** a) Is the R&D plan properly directed at addressing the primary technical and cost risks in an effective manner? b) Are the risks appropriately prioritized and will the completion of the R&D plan provide a basis for proceeding to the construction phase with confidence that performance goals can be met? c) Is the R&D program proceeding satisfactorily toward a construction start near the end of the current decade?

3. **India Collaboration:** Is the program, and division of responsibilities, outlined in the Joint R&D Project document well aligned with the needs of PIP-II, and will it support a construction start encompassing both U.S. and Indian deliverables?

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 April 15, 2016.