Report from the 16th Meeting of the Accelerator Technical Advisory Committee for the Japan Proton Accelerator Research Complex (J-PARC)

February 23 - 25, 2017
J-PARC Research Building
Tokai, Japan

Introduction

The Accelerator Technical Advisory Committee (ATAC) for the J-PARC Project held its sixteenth meeting February 23 to 25, 2017, at the J-PARC Research Building in Tokai, Japan.

The ATAC members participating are: Alberto Facco (INFN), Simone Gilardoni (CERN), Alan Letchford (STFC), Akira Noda (NIRS), Thomas Roser (BNL, Chair), Jie Wei (MSU), and Robert Zwaska (FNAL). Michael Plum (ORNL) and Subrata Nath (LANL) could not attend this year's meeting.

The ATAC thanks the J-PARC management and staff for their hospitality during this meeting, and all the presenters for their excellent and comprehensive talks. The Committee also greatly appreciates that the J-PARC team has addressed all recommendations from the previous report.

The J-PARC facility has operated very well during the last year with a strong emphasis on the users program. The new high-power MLF target was not yet available for installation. To not endanger the present target the beam power to the neutron spallation target was limited to 150 kW. However, steady operation of MLF paid off with a very significant number of science results produced. The MR delivered beam on target for the T2K neutrino experiment with an availability of 69% during the last year. Several equipment failures are still impacting reliable operation of the MR. The reliability improvement efforts of the J-PARC facility should be strengthened to achieve the high level of availability that is expected from this world-class user facility.

R1: Focus on addressing reliability issues at the J-PARC facility.

The MR beam power for fast extraction has steadily increased over the last few years and reached a new record of 470 kW recently. To reach the phase 1 design goal of 750 kW and to keep the T2K neutrino experiment internationally competitive it is critical that the new MR power supplies are constructed and installed in a timely way.

The main delays in the procurement of the new power supplies are related to the limited budget availability, while the construction of the service buildings is well advanced. The project is presently delayed by at least one year to accommodate the budget shortfall.

R2: Procure, construct, install and commission the new MR power supplies and start operation at the faster repetition rate as soon as possible.

J-PARC accelerator overview and projections:

The J-PARC accelerators have now approached their design intensities, but still operated at reduced power due to issues with the MLF and slow extraction target systems. The RCS has demonstrated 1 MW equivalent beam to the MLF and operated above 500 kW, but operation over the last year has been limited to 150-200 kW. The MR has delivered 470 kW to T2K, which is equivalent to more than 750 kW with the MR power supply upgrade. The MR has also delivered 42 kW of slow extracted beam power and is ready for 50+ kW operations when the target limits are lifted. J-PARC has now placed greater priority on operations and reliability to fully exploit the existing capabilities, while still working on facility upgrades, in particular the MR repetition rate upgrade.

RCS for MLF:

- The RCS has proved 150-200 kW to the MLF in the last year, having previously provided over 500 kW and demonstrated capability of 1 MW. The power limitation of the MLF target has limited operations during this period, and will for an extended period.
    - 2073 hours of beam delivery were achieved out of 2259 scheduled for the MLF. The downtime was dramatically reduced from prior years. J-PARC has adopted 90% as a goal for availability, 93% availability has been achieved during JFY16 to-date.
    - 1 MW remains essentially demonstrated, but awaits a MLF target that can handle this beam power.
    - For the near term, operation may be limited to 150 kW until summer, when a target capable of 600 kW will be installed. 1 MW target version is possible one year later.
    - Single-bunch operation of the RCS has been implemented while operating at these lower intensities. This mode provides significant improvement to some users such as the muon facility and some neutron instruments. It is not scalable to higher power, but is a notable innovation to improve beam quality while beam power is limited.
- 1 MW equivalent beam operation was further refined this past year.
    - Studies continue to suggest that 1 MW is available for MLF. Refinements are to limit losses and improve availability.

MR with fast extraction for neutrinos:

- Beam intensity increased to 470 kW in JFY16, exceeding the projections presented at the previous ATAC. Further intensity improvements will be modest until the major upgrade of the magnet power supplies. Running time to T2K was prioritized in JFY16, resulting in excellent neutrino production.
    - Beam power to T2K increased from 394 kW to 470. This beam intensity is equivalent to 900 kW if the cycle time were 1.3 s, instead of 2.48 s.

  - 1803 hours of beam were delivered out of 2602 assigned hours, for an availability of 69%, well below the 90% goal. Both accelerator and neutrino facility issues contributed to the downtime.
  - Studies with higher intensity beam continue to show promise for modest beam power increases previous to the power supply upgrade. The mid-term plan cites 480-500 kW in JFY17 and >500 kW in JFY18.
- J-PARC has begun implementation of a plan to reduce the cycle time to 1.3 sec as its primary path to achieving more than 750 kW in the MR. This is the most straightforward path to upgrading the MR fast extraction program and the Committee strongly supports it.
  - MR RF cavities are nearly fully upgraded to provide more voltage. Cores exist to provide the additional voltage and 2nd harmonic when needed.
  - A fraction of the funding has been committed for the major upgrade of the MR magnet power supplies. The buildings have started construction along with a "first article" of the bending magnet supplies. This investment will take about three more years to realize, such that the cycle time may be shortened to 1.3 sec by the end of JFY19.
  - Along with further improvements to the beam intensity in the RCS and MR, beam powers beyond 1 MW may be possible, perhaps up to 1.3 MW. The mid-term plan has been updated to expect 700 kW in JFY19 and 800 kW in JFY20, with a roadmap to 1060 kW in 2022 and perhaps up to 1.3 MW in 2024.

MR with slow extraction to the Hadron Facility:

- Beam of up to 42 kW was delivered to the Hadron Facility in JFY15.
  - Slow extraction was assigned limited beam during JFY16. 515 hours of beam were delivered out of 612 scheduled, for an availability of 84%, less than the J-PARC goal of 90% availability. Accelerator issues dominated the downtime.
  - Beam quality improved in JFY16, such that up to 42 kW with excellent efficiency (>99.5%) and improved duty factor (>52%) by control of instabilities and implementation of extraction feedback was achieved.
  - Studies at 50 and 60 kW were promising. The administrative limit on the present target will be lifted slightly to allow regular 50 kW operation. Further increases will require upgraded targets and better loss control in the slow extraction process.
  - The mid-term plan quotes a goal of 50-60 kW in JFY18, and 60-80 kW in JFY19, increasing to 100 kW in 2021 or 2022.

J-PARC plans to operate the MLF for 176 days in JFY17 and operate the MR as much as funding allows electricity to be purchased. The split between FX and SX was not yet determined.

Downtime in the accelerators was due to collimator vacuum failure, critter infestation of a transformer, and three unconnected grounding failures (leading to component failures).

J-PARC is considering extending their beam cycle from the present 44 days to 70 days, so as to improve the availability to users. Between each cycle is a 2-3 day period for replacement of the ion source, recommissioning, and machine development.

Initial work has occurred to develop a plan to strategize for maximum science output. Approach is to focus on: scheduling, availability, beam power, beam quality. Resources and investments in reliability improvements limit the availability. An additional strategy is to implement an "anomaly detection system"; this study is just starting. Higher beam power is equivalent to improved efficiency as beam loading contributes negligibly to electricity consumption. Higher beam quality may be achieved with single-bunch operation of the RCS, but only at modest beam powers. Single-bunch beam produces superior neutron and muon beams (shorter pulse duration).

Comments:
The MR already has two independent operating modes: fast extraction for the neutrino users and slow extraction for hadron users. In 2019, COMET will require a third mode of operation. The MR operating hours will need to be carefully split among these three modes of operation. Consideration might be given to simultaneous or interleaved operation of these three modes (interleaved beam cycles) to serve different types of users. It might also be possible to keep users that need a mode of operation that is different than the running mode on standby. For example, the neutrino facility suffered about 16 days of downtime this January during which the MR could not provide beam to users. If a hadron user were available, that beam time could have been recovered. Planning and control system work might be required to interleave two or more modes of operation.

R3: Explore the possibility of increasing the flexibility of MR operation to make more efficient use of the facility and serve more users.

There were at least two cases during the last year at J-PARC where the Machine Protection System (MPS) failed: the collision of the RCS collimators and the beam induced vacuum leak in the MR abort beam line. These incidences might indicate that the MPS is not comprehensive enough. The whole MPS architecture, approach, and management should be reviewed for completeness and whether it sufficiently protects the equipment from damage under all failure scenarios.

R4: Review the whole J-PARC Machine Protection System and present the result at the next ATAC.

There were also a couple of incidences where the grounding of equipment was inadequate and equipment was damaged as a result. Proper electrical grounding is essential for the safe operation of high power equipment. The grounding scheme, implementation, and electromagnetic compatibility of all equipment of the J-PARC facility, both existing and planned, should be examined.

R5: Examine the grounding scheme, implementation, and electromagnetic compatibility of the J-PARC equipment.

Linac status and beam studies

Findings:

- During 2016 the linac stably delivered 40 mA beam intensity for user operation, increasing performance from 2015.
- The overall linac availability was rather high, above 90%, although affected by an increased number of short stops caused by RFQ trips and stops from MPS triggered by anomalous BLM behavior. Several stops were caused by failures of the anode modulators. Except for the RFQ trips, the causes of the stops have been mostly identified and plans to fix them have been developed.
- Issues, which were still present in 2015, have been properly addressed and most of the limitations that they caused have been removed. Cooling water flow reduction, although not yet critical, was tackled successfully. A complete understanding of the problem has not yet been achieved. Work on this aspect is continuing.
- Klystrons have operated reliably, in spite of their age, especially the 324 MHz klystrons. Four klystrons have been replaced and an adequate number of spares has been made available.
- Beam studies answered several questions related to beam losses and improved linac performance and system comprehension.
- Operation in 2017 is expected to further improve both in performance and availability and the linac operation appears to support the planned upgrades.
- <u>The Committee congratulates the linac group for their remarkable achievements.</u>

Ion Source and RFQ

- The ion source reached 1337 hours of continuous operation at 45 mA, without failures all year and a spark rate of less than one per day. The SNS internal antenna worked reliably with a long lifetime.
- RFQ operated in a stable way at 40 mA, with18 trips/day, each causing a 1-minute stop. This resembles the very good RFQ behavior during 2015, but with an increased beam current.

Comment:
The MPS triggered RFQ stops are still numerous and are contributing significantly to the integrated downtime. The physical origin of the RFQ stops and whether they are caused by internal sparks or by the control system itself is not yet fully clarified and should be better understood to improve availability and to prevent future problems.

R6: Investigate the origin of the frequent RFQ trips.

DTL/SDTL

- The residual multipacting problems in DTL cavities have been solved. Cleaning with acetone of the RF surface cavities S05A, S06A, and S06B was done in 2016, and has eliminated or reduced the multipacting to tolerable levels, confirming expectations. Now all cavities are operating regularly with no issues. The trip rate is now below the very comfortable level of 0.5/day.

Cooling issues

- Cooling water issues causing beam stops lasting several hours, temporarily fixed in 2015 by adjustment the regulating valves, have been investigated to prevent a possible clogging of the cooling pipes of cavities and magnets in the low energy section.
- Obstructions in the DTQ magnet cooling pipes caused by contaminant particles have been found by means of a fiberscope and fixed by removal of the foreign material. Following this result, all remaining DTQ pipes will be examined and cleared during 2017.
- Clogging of SDTL-Q was caused by material identified as copper oxide, which was eventually removed.
- As a measure to improve the water flow rate, the cooling system was split into two parts and an additional water pump was installed.
- These actions allowed the restoration of a correct flow until one of the two water pumps of the system collapsed, spreading micron-sized steel particles in the circuit. These particles were magnetized while travelling in the system quadrupoles, collecting in larger clusters and sticking in flow meters and elsewhere in the circuit. Flushing could partially remove particulate and restore operation. A more drastic and hopefully conclusive cleaning is planned during the summer stop.

Comment:
A better understanding of the water-cooling problems has been reached and mitigating measures have been taken. Further interventions are being planned. However, the presence of copper oxide and metal particles in the water suggests that a stricter monitoring of the water quality and installation of additional filtering might be required.

ACS

- ACS operation was stable at specified parameters and resulted in better cavity conditioning: trip rate, already low in 2015, was further reduced by 2/3 with no problems.

Beam Chopper System

- Ringing problem in the double chopper system has been completely solved by independently powering the two resonators.
- Chopper was operated at 40 mA beam for 9 months. Shallow, 0.15 mm deep craters were observed on the scraper surface; this was to be expected and should not be considered risky.
- Fulfilling previous recommendations, a test stand including ion source, RFQ and chopper, dedicated to long term testing of the chopper system at 50 mA of beam current and above, was realized and beam experiments have started. The Committee looks forward to hearing about the results at the next ATAC meeting.

Bunch Shape Monitor (BSM)

- New BSMs with improved vacuum behavior and reduced pumping requirements were developed. Units have been installed at MEBT1 and ACS1 sections and operated successfully. The foreseen vacuum improvement was effective. Beam studies with the use of these components have started. Replacement of all the old BSMs with new ones is on-going.

RF system

- Many of the 324 MHz klystrons exceeded 50000 hours of operation. Three of them have been replaced and 10 spares are now available. Most of the 972 MHz klystrons reached 20000 hour of operation, one was replaced in 2016 and 5 spares are available.
- Although some of them are rather old, the klystrons continue to operate reliably and the number of spares appears to be adequate at the moment.

Comment.
A rapid decay of performance due to aging is, however, to be expected at some point. This must be anticipated, taking into account the time to procure new or refurbished klystrons, to avoid long operation stops.

- Flaws of anode modulators related to the high operation temperature are being addressed. The decision of building new, more simple and reliable ones with lower, but still adequate, stability specifications seems to be a good choice.
- The construction of the klystron test stand, now on-going, will facilitate off-line conditioning and performance testing without negatively interfering with linac operation.

Alignment

- Significant ground movements continue over the years and are being properly monitored. Re-alignment of the linac has been performed in 2016 restoring optimal conditions.

Beam loss mitigation

- Following the good preliminary results obtained in 2015, aiming at minimizing beam losses caused by Intra Beam Stripping (IBSt), linac beam studies were carried out in 2016. Simulation and beam experiments were performed to find an optimum compromise between minimum emittance growth and minimum IBSt. Different operating points with reduced transverse focusing in comparison with the original beam dynamics design have been analyzed, resulting in the possibility of reducing IBSt by 40% to 60% but also possibly causing beam resonances and instabilities. Stable beam transport could be restored in some cases by relaxing the longitudinal focusing as well. Good operating points have been found as possible candidates for stable operation. Very promising beam trials were performed at a 95% ACS tank level and $T_x/T_z = 0.3$, mitigating IBSt losses by more than 50%.

Comment:
The studies performed on IBSt beam loss mitigation are giving very promising results and are of great importance for understanding the linac performance limits in view of the planned beam current upgrade.

60 mA upgrade beam studies

- Fulfilling a previous ATAC recommendation, the ion source beam phase space have been measured at the test stand at 66 mA and the real beam distribution has been used in RFQ simulation for the 60 mA current upgrade. The resulting measured emittance ($\varepsilon_{x,y}$=0.27 mm mrad) is consistent with the RFQ acceptance and matching can be achieved with the present, 2-solenoid LEBT configuration. Simulation with a realistic beam distribution showed RFQ transmission and output emittance according to previous assumptions. There are no showstoppers for the 60 mA upgrade coming from the source-RFQ system.

Status of RCS and beam study results

Findings

With no spare target to install in 2016, the MLF beam power has been limited to 150 kW. 700 kW equivalent beam has been delivered to MR.

In April 2016 a control system failure resulted in collimators being driven into each other. The collision of the blocks cracked an electron beam weld between the flange and support leading to a vacuum leak. The broken collimator was replaced with a temporary beam duct until summer 2016 when a fixed collimator was installed. During the period of running without the collimators some increased activity was observed at the high dispersion areas but this was deemed acceptable. During the repairs 24 workers received a total dose of 0.620 man-mSv with a maximum individual dose of 60 μSv. An improved control system with better monitoring of collimator positions and collision avoidance will be implemented.

In order to mitigate vacuum pressure rise during high power operation, which may lead to increased beam loss, an in-situ bake of the kicker magnets has been implemented. The challenge is to achieve sufficient temperatures in the Al alloys and ferrites (> 120 C) with low temperature rise (< 30C) in the ceramic vacuum vessel to prevent damage due to excessive thermal expansion. Careful thermal management has achieved these goals resulting in an order of magnitude improvement in the vacuum pressure to 10^{-6} Pa after baking for ~100 hours.

An absolute calibration of the BLMs has been performed using the residual induced activity.

Workers' collective and peak radiation doses have been reduced over previous years: 2 man-mSv in 2016 compared to 4.5 man-mSv in 2015 with a maximum individual dose of 0.2 mSv compared to 0.4 mSv. This is largely due to the low power operation, a better foil procedure, and no requirement to carry out work in the injection straight.

MLF running contributes most to RCS equipment activation due to the larger number of pulses. To reduce this activation, the foil scattering losses should be minimized. Maximizing MLF target lifetime requires a large emittance beam. To achieve these two requirements the injected beam is painted to 200 π mm mrad transversely. During the phase space painting the resonance $\nu_x+2\nu_y=19$ is crossed. This resonance is excited through a distortion of the lattice super-periodicity caused by the edge focus of the injection bump magnets. Use of the quadrupole correctors compensates for the edge focus and reduces the effect of the resonance. The injection painting also passes close to the $2\nu_x-2\nu_y=0$ resonance, which leads to emittance exchange between the horizontal and vertical planes. With anti-correlated painting the painting is in the same direction as the emittance exchange, which mitigates the emittance growth form the $2\nu_x-2\nu_y=0$ resonance, leading to only 0.2% loss compared to a 2% loss for correlated painting.

MR operation requires a low emittance beam with small halo. The smallest beam width is achieved for an injection painting of 50 π mm mrad. Unlike the large painting case, correlated painting achieves the lowest emittance growth for this small painting. Numerical simulations have shown how for the small, slower painting, anti-correlated painting leads to synchronism between the painting and emittance exchange producing a deflection of the charge density and a resulting larger space charge tune shift. Correlated painting avoids the synchronism and results in higher charge density. Experimental measurements have confirmed the simulation results.

Significant emittance growth is observed until 6 ms after injection for the 50 π mm mrad painted MR beam due to the $\nu_{x,y}$=6 and $2\nu_x-2\nu_y$=0 resonances. Manipulation of the tune and chromaticity separates the beam from $\nu_{x,y}$=6 and minimizes emittance growth but excites an instability later in the cycle due to the kicker magnet impedance. Simulations indicated that introducing large negative chromaticity would eliminate the instability but requires bipolar sextupole magnet power supplies. The new power supplies were installed in the summer 2016 maintenance period and subsequent measurements confirmed the simulation results.

The existing quadrupole correctors only operate during injection. In order to generate the optimum tunes for both MLF and MR running on a pulse-by-pulse basis requires them to operate through the whole cycle. It is planned to upgrade the corrector power supplies to achieve this in 2017 or 2018.

Comments
The damage to the RCS collimators was avoidable. The team should fully evaluate all possible operational scenarios for the new control and protection system to ensure that the collision of collimators cannot occur under any circumstances in the future.

The Committee was impressed by the quality of the RCS simulations and the degree to which they agree with measurements. The explanations for why the different painting schemes work was very convincing. Reducing beam loss to 0.2% for such a high intensity machine is a very significant achievement.

The Committee endorses the plan to upgrade the trim quad power supplies to allow pulse-by-pulse tune adjustment for MLF and MR operation.

Status of MR.

Findings
MR regular operation at 30 GeV was focused on beam production for neutrino and slow-extraction physics.

- The regular operation for the FX at 390 kW has been realized during 2016, with an increase to 470 kW already in February 2017. The operation of the SX was at 42 kW.

- Accelerator faults caused beam un-availability to the FX users of 14% during 2016, whereas of only 4% during the first two months of 2017.

A number of technical incidents occurred during 2016 run, all uncorrelated but leading to a noticeable loss of beam time.

- A failure in the Fast-Abort extraction system triggered an extraction to the abort beam line on a wrong trajectory. The beam intercepted a flange and the vacuum seal of a ceramic brake, causing a vacuum leak. The failure was due to noise from the septum power supply grounding, which in turn caused the control system to trigger an extraction to the abort line with an insufficient strength of the extraction septum.

- The main dipole BM-67 suffered from a water leak that damaged one of the coil insulators and induced a short circuit. The magnet was replaced with its spare. It is not clear, however, what caused the leak, but it might be related to a water-cooling pipe brazing.

- A short circuit of transformer of the injection septum magnet was caused most probably by the invasion of an animal in the active part of the transformer. Similarly to what happened at other facilities, it is very difficult to predict this kind of incident and to implement generic protective measurements against the intrusions of wild animals into machine equipment that have to be necessarily installed outside the service buildings, like large transformers or power supplies.

- The power supply for the new injection septum installed for the future 1.3 s operations had an electrical failure. Due to larger noise from grounding, some IGBTs of the AC-DC converter stage auto-triggered, causing large damages to other IGBTs from the uncontrolled capacitor bank discharge.

- The transformer in the power supply for the RF cavity in the D3 building suffered from overheating. A power converter was not shut down by the control system when not in use due to large electro-magnetic noise from grounding. This problem could be fixed by adding a second grounding point.

Comments

The problems causing the vacuum leak in the abort line seems to be fully understood and the implementation of a new grounding cable solved the issue completely. This incident, however, identifies two possible risks for other systems:

First, it is not clear if the protection offered by the MPS is sufficient, both for the hardware and in its implementation in the control system. It seems that the interlock system is not able to recognize the fact that the septum was not correctly charged. Also, it is not clear what the reaction of the MPS is in case an extraction is triggered when the extraction elements are not correctly charged.

Second, as in the case of the IGBT issue and the RF power supply overheating, the grounding of the power supply seems to be insufficient as is the shielding from EM noise. This was the cause of three major issues during the last run.

Following the water leak causing the short circuit of the BM-67, a campaign to monitor the status of water manifolds of the main magnets has started. It would be important to understand if this incident constitutes the first sign of a systematic weakness in the cooling pipe brazing that is appearing after some years of operation. The investigation of the cooling system should not be limited to the main dipoles, but extended also to the main quadrupoles.

R7: Monitor the condition of the brazed joints of the cooling lines of the coils of all MR magnets.

The magnet replacement took about two weeks. It is important to understand if the duration of this operation could be reduced.

While it seems that the AC-DC stage of the new MPS has sufficient redundancy and protection, it would be advisable to verify if an accident similar to the auto-triggering of the IGBTs in the new septum power supply could occur. A statistical analysis of the IGBTs auto-triggering, from electromagnetic noise or other sources, could be done to assess the risk of failure for the new septa power supplies but also the future MR power supplies.

MR Beam studies and MR upgrade plan

Findings

Since the beginning of the year the MR is delivering routinely 470 kW, thanks to the improvements realized during the last year.

The beam studies concentrated on loss reduction and the optimization of the loss management. By tuning of the collimators, local bumps, RF tuning and resonance corrections, the residual radiation has been successfully reduced.

The optimization of the injection starts with the optimization of the working point of the RCS, requiring a re-matching of the 3-50BT transfer line.

The beta function beating, caused by the leak field of the injection septum, has been reduced to below 10%.

The transverse tune working point was changed from (22.40, 20.75) to (21.35, 21.45) to operate sufficiently far away from the integer, half-integer and other detrimental resonances. This allowed pushing the maximum power beyond 420 kW while maintaining low losses.
The correction of the 3rd order resonances was implemented with this new working point, improving beam transmission, whereas the linear coupling correction did not bring any gain.

During FX operation at 470 kW total cycle losses were less than 794 W, localized at the location of the betatronic collimation system. These losses are well below the limit of 2 kW that can be accepted by the current collimation systems and the doses on contact, registered in the rest of the ring, are below 2 mSv/h.

Tests at 496 kW showed that losses increase to 1079 W and are still manageable by the existing collimation system, but with a net increase of losses in other ring sections, in particular in the large dispersive region. Such beam losses would not be tolerable for nominal beam power operation of 750 kW, considering also that the collimators would have to absorb a beam power close to or beyond the 2 kW limit.

Studies were done with a beam intensity of 3.6×10^{13} ppp in two bunches, that would correspond to 1 MW beam power with 8 bunches (2.9×10^{14} ppp) and the faster ramping cycle. Total losses in this case were about 350 W that extrapolated to 2.6 kW for 1 MW operation.

Issues for the proposed upgrades to reach operation at 2.9×10^{14} ppp are: longitudinal beam stability; improvements of the collimation system; addition of anode power supplies of RF cavities (planned for JFY-2021); and reduction of beam losses in the FX region.

Dipole coupled bunch instabilities (mainly mode 8) are observed all along the cycle for beam powers beyond 470 kW. The main cavities are the impedance sources of the instabilities. The impedance can be reduced effectively with a one-turn-delay feedback, already used at other facilities, and the use of the main cavities as longitudinal kickers. Losses and their localization were also optimized with the second harmonic RF voltage.

Two new collimators that are adjustable in position and angle were installed to improve the collimation efficiency and localize the losses. A net improvement was observed due to the angle optimization. Two more collimators will be upgraded with this new functionality.

A transverse beam scraper (1 mm thick plate of tungsten) was installed to test a scatterer & catcher (2-stage) collimation scheme. The catcher would intercept the beam halo generated by the scatterer. Preliminary tests, despite the difficulties from using an empirical set-up, seem to indicate an improvement in loss localization.

Losses in the FX region were already presented during the ATAC-2016 and the proposal of introducing larger aperture quadrupoles still remains valid.

According to the recommendation of the ATAC-2016, the BLMs have been calibrated with the measured residual dose rate.

A roadmap towards operation beyond 1 MW (with a target of 1.3 MW) was proposed, which includes a tenth FT3L RF cavity, a further reduction of the cycle length from 1.3 s to 1.16 s, a BPM upgrade in speed and accuracy, and a FX kicker upgrade with less impedance (optional).

The Committee would like to stress that the machine studies and upgrade plans should be focused on the final goal of reaching the nominal phase-I performances, i.e., regular operation for the neutrino FX at 750 kW.

The Committee takes note that the studies for multi-MW projects already presented during the ATAC-2016 are continuing.

Comments
The action proposed to mitigate the effect of the longitudinal coupled bunch instabilities seems to be sound. However, it is not clear yet if residual quadrupole oscillations are also present and if they could be detrimental once the dipole motion is damped. Studies should address also this issue, since a different LLRF system for the longitudinal feedback will be needed or they might require a Landau damping RF cavity.

The improvement of the beam loss management was obtained with the optimization of the collimators adjustable in position and angle. This optimization, however, risks depending on the pulse-to-pulse variation of the closed orbit at the location of the collimators. Further sensitivity studies of collimation efficiency versus the closed orbit should be pursued. Eventually, a semi-automatic alignment system for the collimators based on BPMs embedded in the jaws could be investigated.

The 2-stage collimation system based on a scraper and absorber seems to be promising in improving the collimation efficiency. It is not clear, however, what is the net gain with respect to the aforementioned optimization of the single-stage collimation system. This should be better clarified with simulations and beam studies.

A 2-stage collimation system requires a certain attention to the collimator hierarchy, i.e., the secondary collimator should always be in the shadow of the scraper. A clear procedure to determine and optimize the relative position of the scraper and the collimators should be defined, by simulations and by beam measurements. Other materials than Tungsten for the scraper should be investigated, in particular low-Z ones like Carbon or Beryllium.

The installation of collimators in dispersive regions should be investigated as an alternative to the 2-stage collimation system.

Impedance and Instabilities

Findings and comments
At the ISIS synchrotron, the transverse tunes are varied during the 10-ms cycle with trim quadrupole magnets on programmable power supplies to (1) compensate for the natural chromaticity and the varying magnetic field at injection, (2) ramp up tunes to minimize effects of space charge depressions during beam capture, (3) reduce tunes during the time from 2 to 4 ms after injection to avoid transverse resistive wall instability, and (4) lower tunes to avoid coupling resonances at extraction. J-PARC RCS now plans to upgrade the power supply to QDT trim

quadrupoles to gain similar benefits. J-PARC RCS sextupole power supplies have already been upgraded to bipolar excitation to enhance instability damping.

The Committee endorses the plan to upgrade the trim quadrupole power supplies. We further encourage the J-PARC team to systematically evaluate the potential benefit of programmable correctors for orbit correction, tune manipulation, chromaticity manipulation, and resonance corrections.

R8: Evaluate the benefit of programmable correctors for orbit correction, tune manipulation, chromaticity manipulation, and resonance corrections in the RCS.

Findings and comments

Electron cloud effects were observed during the slow extraction debunching process in the MR. Also, during beam studies in the MR a single-bunch instability in the vertical direction was observed with signatures found in electron cloud instabilities including head-tail modes and frequency spectrum. As electron clouds can limit the performance of high intensity and high power operations, understanding of its onset conditions and available mitigation methods is important.

We encourage the J-PARC MR team to perform an analysis of the effects and causes of electron clouds starting with numerical simulations and benchmarking them with machine studies using the available diagnostics including electron detectors. We also encourage the team to consider mitigation techniques used at other facilities on both source elimination, including surface coating and beam scrubbing, and as well as increased Landau damping. An example of the latter is increasing the momentum spread by placing the beam on the unstable fixed point before debunching.

Status of MR Slow Extraction

Findings and comments

Slow extraction efforts in the MR continued well during the last year with good efficiency, improved beam power and duty factor, but with limited operating hours and availability.

- 42 kW has been supplied for slow extraction user operation (duty factor: 52 %, Extraction Efficiency > 99.5 %). The accelerator is ready to provide more beam power as administrative limits are lifted and the target is eventually upgraded.
- Slow extraction availability was 84.1% over 612 assigned user hours during JFY16 to-date. The reduced availability was due to accelerator failures. The goal for the availability is 90%.
- Extraction studies have been performed at 50.8 kW with a duty factor of 55% and excellent efficiency of 99.5%. The administrative limit on the target power will be increased to 53 kW in the near future, allowing operation in the 45-50 kW range.
- Initial studies with a beam power of 66 kW are also very promising. With the faster Main Ring power supplies, this beam intensity is equivalent to ~ 100 kW. With

additional loss control, the MR could be capable of delivering 100 kW to the hadron hall when the MP PS upgrade is completed.

The extracted beam profile and position is monitored and well maintained throughout the extraction process. The stability is achieved with dispersion and an achromatic dynamic bump.

Intensity-dependent effects were a particular focus during the last year. Beam was observed to go unstable during the debunching process. During the instability electron clouds were directly observed via electron detector as well as a ring-wide vacuum pressure rise. Longitudinal smearing with a phase offset at injection cured the effect. However, studies showed that higher intensity required a larger phase offsets. A further potential mitigation would be to move the beam temporarily onto the unstable fixed point before debunching increasing the dp/p and hopefully suppressing the instability.

Beam spill regulation was improved. Feedback quadrupoles quickly respond to ripples in the main power supply. Transverse RF with a higher power has allowed the duty factor to increase by 8-10%. A spill monitor with new scintillator and photomultiplier has further improved the duty factor.

Residual activation was measured and is substantial, as much as 9 mSv/hr. This is comparable to last year's level, but runtime has been limited. Further mitigation of residual activity will be achieved with the installation of a titanium-ducted electrostatic septum, which is expected to reduce the activity by a factor of 5. This approach is likely effective in the short-term, but should be analyzed for the long-term as certain long-lived isotopes might be preferentially produced in titanium (e.g. Scandium-46). RF shields for septa have been installed and dramatically reduced the impedance. The titanium ESS awaits an RF shield for installation. When considering 100 kW operations, further efficiency improvements and loss reduction must be achieved to keep residual activation tolerable. Additional shielding may also be needed. A quantitative analysis or plan was not presented.

Slow extraction for the COMET experiment is being tested. Phase-I requires 3.2 kW beam power at 8 GeV (2019). Phase-II is 56 kW at 8 GeV (2023). The COMET beam pattern in the MR will use a 3-bunch pattern, with the other 6 empty buckets requiring a very high level of extinction. An issue with the extraction of 8 GeV beam is the larger geometric emittance. Phase-I can be achieved with reduced transverse painting in the RCS. Initial tests have verified that a beam can be produced at the MR flattop at 8 GeV with similar transverse profile as at 30 GeV. Phase-II will require larger aperture septum magnet with a new power supply.

Excellent extinction of the empty RF bucket in the RCS was demonstrated by mistiming the extraction kicker pulse to prevent transport to MR. This achieves an extinction of 10^{-11} or better. However, a similar extinction of empty RF buckets has not been demonstrated in MR with 3-bunch operation. As long as beam is lost during acceleration there is the possibility of beam migrating between buckets. Studies of this extinction should be prioritized and schemes to mitigate out-of-time beam considered (for example, anti-damping). Space charge simulations of COMET beam have started.

A beam power of 50 kW for the SX mode, the goal of the first phase, has essentially been realized. Demonstration of the needed intensity has been very successful, user operation at 50 kW only awaits the administrative limit on the target being lifted to 53 kW.

Linac and RCS upgrade

Findings

Two upgrade plans were presented: increasing the RCS power from 1 MW to 1.5 MW and doubling the linac repetition rate to 50 Hz for a Transmutation Experimental Facility (TEF).

Increasing the RCS power to 1.5 MW requires 60mA injected current for 0.6 ms. This means 70 mA is required from the ion source. An ion source current of 66 mA had previously been demonstrated but with a significant current droop. Recent R&D has shown that removing N_2 & Ar impurities in the plasma gives the same current with no droop, a 10% smaller emittance and requires only 24.6 kW of RF power compared to 40.6 kW.

After one year of simulation effort no progress has been made in reducing the linac beam loss for 60 mA operations. The main causes of loss are the limited DTL apertures and intra-beam stripping in the ACS and first arc section. With 50 Hz operations for TEF this could result in a fourfold increase in the loss levels although it would still be below 1W/m.

To achieve a 600 μs injected pulse requires an 800 μs RF pulse from the klystrons. The resulting capacitor bank droop means the cathode voltage drops from110 kV to 103 kV, reducing the output power from 2.47 MW to 2.22 MW across the pulse. The maximum power required from a klystron at 60 mA beam current is 1.89 MW in SDTL16.

The requirements for the TEF are 133 kW chopped in the first stage and 250 kW un-chopped in the second stage. Alternating 50 Hz pulses from the linac are sent to the RCS and TEF using a separator. The main issues raised by operating at 50 Hz are beam loss, klystron AC power and water-cooling capacity. The klystron HVTR is rated at 1000 kVA but 1154 kVA is required for 50 HZ at 600 us. An auxiliary PSU is planned. An increase from 6 to 8 water chillers is required to operate at 25 Hz, 60 mA and 600 us for 1.5 MW. Doubling the repetition rate to 50 Hz requires a further increase from 8 to 10 chillers.

A pulsed magnetic separator is proposed at 400 MeV in the L3BT line. The bending magnet kick angle is limited to 50 mrad to restrict Lorentz stripping. This angle is insufficient to steer the beam past QM3 & 4 so the deflected beam must pass through them. The current QM aperture is not large enough to allow this so the design of new, larger aperture magnets is ongoing. The residual field of the pulsed bending magnet, estimated at 3 Gauss, distorts the orbit of the un-deflected beam towards the RCS so DC correction magnets are needed. A laminated 0.32 T 1600 A pulsed bending magnet and 0.034 T correction magnets have been built. The measured DC fields agree well with Opera3D.

At 1.5 MW operations it may be hard to avoid instabilities without reducing the kicker magnet impedance. The possibility of controlling the instability with the present bipolar sextupole PS is being investigated.

A redesign of the injection straight to allow for extra shielding and bellows for improved maintainability is underway. Reducing nuclear reactions in the foil means limiting the foil hits. Increased painting and a reduced foil width can bring the foil hits down from 41 to 7 per injected particle. With the increased average current the total number of foil hits increases from 91.1×10^{13} at 1MW to 116.6×10^{13} at 1.5 MW. Dose rates greater than 20 mSv/h are possible so additional shielding is required. To make space the separated bump magnets will be joined making 710 mm available for the extra shielding. 200 mm of iron shielding gives a surface dose rate of 0.15 mSv/h after 30 days operation and 1 day cool down. Eddy current heating of the iron shielding is being investigated.

Even with the reduced hits the foil may not survive beyond 1 MW so a smaller, thinner foil is required. The foil temperature will be reduced but the flux of H_0 at the dump increases. Scrapers in L3BT will be required to limit the H_0 load on the dump to 4 kW.

The RF anode PS current limit of 146 A is already close to the requirement for 1 MW. To operate at 1.5 MW reducing anode current will be necessary. This can be achieved with higher impedance FT3L cores and a higher resonant frequency. FT3M cores and a frequency of 1.7 MHz requires 212 A for 1.5 MW. FT3L cores and a frequency of 2.5 MHz requires 146A, just within the PS limit. R&D on the necessary beam compensation feedback has started.

Comments

The Committee commends the ambition of the upgrade plans. These will require expensive hardware upgrades but there appear to be no insurmountable problems except possibly the increased beam losses. Although anticipated to still be below acceptable levels, efforts to reduce it further should be continued.

The resources spent on exploring facility upgrades should be commensurate to the anticipated time frame and probability of the realization of these future upgrade opportunities.

New injection and fast extraction systems from MR

Findings and comments

The coil vibration problem of the new injection septum has been solved by careful treatment during assembly process, removing the possibility of future damage from metal fatigue.

The effect of the iron beam duct on the fringe magnetic field should be clarified. The required wide aperture quadrupole doublets should be designed in much more detail in order to enable beam optical calculation.

The first magnet of the new fast extraction low field septa has been fabricated in 2014. Its design and results from field measurements should be reported at the next ATAC.

The high field septa construction is well under way but tests at 1.3 s cycle time still need to be performed.

<u>New power supplies of MR</u>

A higher repetition rate for the MR, reducing the cycle time from 2.48 s to 1.3 s, is necessary to reach the original beam power goal of 750 kW. The construction of prototypes has been successful and the construction of one out of the six Bending Magnet modules as a first article is proceeding well. Close attention should be paid to noise affecting the IGBT-based high power switching circuit. The team is staying in close contact with the fabrication companies and other institutions with relevant expertise such as CERN.

The new MR power supply system has been separately developed at a company and KEK. The use of an optical linkage separates ground level between control system and high power system.

A division of the container into different compartments per frames should be carefully investigated to avoid the complete destruction of a capacitor bank container in case a single frame catches fire.

The quality and the conformity to specification of the capacitor banks should be verified after delivery to J-PARC and before the assembly, for example, of a full container to identify any possible weaknesses that might cause damages during operation.

R9: Implement acceptance procedures of the capacitor banks as part of the quality assurance process.

Given the high modularity of the power supplies, it would be wise to identify connection schemes to enable operation, even in degraded conditions, in case of one or more frames are unavailable or under maintenance.

R10: Define degraded modes of operations for the new MR power supplies.