BEAM COMMISSIONING OF THE J-PARC MAIN RING*

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Abstract

The first stage of beam commissioning for the J-PARC main ring (MR) was carried out in May and June of 2008. A 3-GeV beam extracted from the rapid cycling synchrotron (RCS) was injected into the MR and circulated with rf capture. At this time, we found a large common mode current flowing in the main magnet power supply cables, which caused large fluctuations both in the beam orbit and betatron tune. Between the first and the second stages of beam commissioning, we changed the magnet supply cabling to reduce the common mode ripple effect. Both the fast extraction and the slow extraction systems were installed during this period as well. The second stage of beam commissioning started on 22nd Dec. 2008 with the goal of accelerating beams up to 30 GeV; and after a short tuning period the beam was successfully accelerated. Both the fast extraction and slow extraction systems worked well. A notable feature of the MR is that it is the first large proton accelerator which has an imaginary transition energy, and beam acceleration was very smooth from injection through to extraction. Several basic parameters of the MR have been measured.

INTRODUCTION

The J-PARC accelerator [1] is composed of a 400 MeV H^- linac (but only 181 MeV initially), a 3-GeV RCS, a 50-GeV MR and related experimental facilities. The RCS provides a proton beam to the Materials and Life science experimental Facility (MLF) to generate intense pulsed neutron beams. A muon target is installed at a position before the neutron target to generate intense muon beams for use in various experiments. A part of the beam extracted from the RCS (4.4% typically) is injected into the MR. In the MR, the maximum beam energy is 30 GeV for phase 1 of the construction. The MR has two experimental facilities: One is a neutrino facility, which uses the fast extraction system and the other a hadron beam facility which uses the slow extraction system.

Beam commissioning of the MR started May 2008. In that run, our aim was to check if there would be any issues for beam acceleration in the second stage (Dec. 2008 to Feb. 2009). At that time we noticed a very large common mode current riding on the output of the power supplies for the dipoles and quadrupoles, resulting in both orbit and tune fluctuations. During the shutdown after the first stage tests, we changed the power cabling configuration for both dipoles and quadrupoles to mitigate the magnetic field fluctuations induced by the common mode current ripple.

The second stage of beam commissioning started 22nd December and first beam acceleration from 3 GeV to 30 GeV was performed the next day. The fast extraction system of the MR is bi-polar: One polarity is for the normal extraction to the neutrino beam line and the other is to the beam abort line which is used to keep imperfect beams out of the neutrino beam line. The beam abort beam line was used during this machine study period.

On January 27th the first attempt at beam extraction into the Hadron beam facility using the slow beam extraction system was conducted and worked well.

MR OVERVIEW

Fig. 1 shows a layout of the MR and experimental facilities. The MR has a three-fold symmetry and a circumference of 1568 m. Each arc section consists of eight 3-FODO arc modules. The arc module has a missing bend cell, which makes for the imaginary transition energy. Three dispersion-free 116-m long straight sections, each of which consists of 3-FODO sections and a matching section, are dedicated respectively to “injection and beam collimation”, “slow extraction”, and “fast extraction and rf acceleration”.

The MR has 96 dipoles, 216 quadrupoles with eleven families, 72 sextupoles with 3 families and 186 steering coils. For the rf system, magnetic alloy (MA) cut-core high gradient broadband cavities were adopted. The number of rf cavities is four at this stage.

The beam diagnostics available during initial beam commissioning of the MR were 186 beam position monitors (BPMs) which can have their measuring circuits switched to be used for either COD or turn-by-turn orbit measurements, 11 current monitors, three transverse profile monitors, 238 beam loss monitors, and horizontal and vertical tune meters.

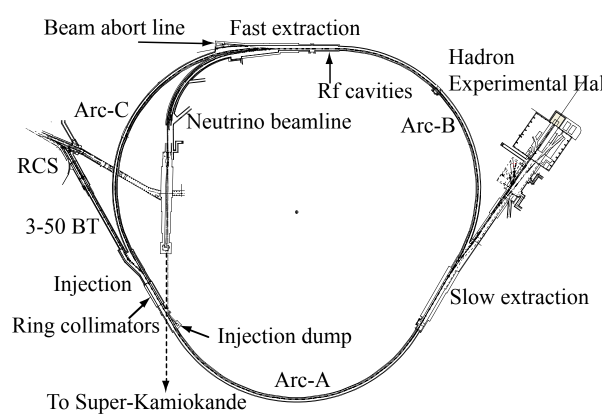


Figure 1: Layout of MR and experimental facilities.

FIRST STAGE BEAM COMMISSIONING

The first stage of beam commissioning took place from May to June 2008. The main purpose of this run was to check for any serious issues with the MR. Injection and accumulation of beams without acceleration were studied. The beam was captured at the center of the rf bucket after frequency tuning. Although quadrupole oscillation due to mismatch between the rf voltage of the RCS and that of the MR was observed, adjustment of the rf voltage of the MR suppressed this oscillation. Measurements of beam parameters such as the COD and the tune number clarified the suspicion that there must be a very large common mode current ripple coming from the power supplies for the bending and quadrupole magnets. Orbital fluctuation due to the current ripple in the dipoles was 3 mm and tune fluctuation due to the current ripple in the quadrupoles was ±0.03. Other than the excessive current ripple from the main power supplies, there were no other serious issues observed.

CABLING NETWORK IMPROVEMENTS

The main power supplies for the dipoles and quadrupoles use IGBT/IEGT switching devices, which make for a compact power supply. However, these very fast switching devices also produce wide band electrical noise. To investigate whether common mode currents were causing fluctuations in the MR beam orbit and betatron tune detailed measurements were taken. Quadrupole field-components measured along the tunnel at various frequencies are shown in Fig. 2 in which clear standing waves are observed.

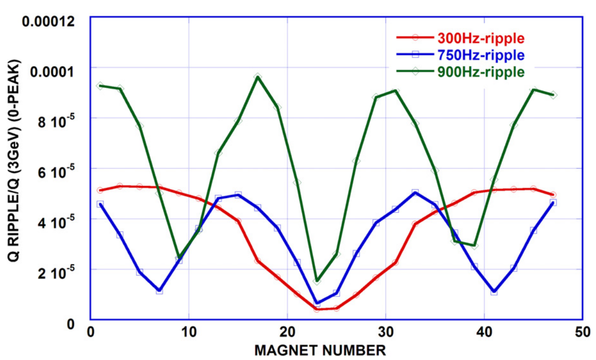


Figure 2: Quadrupole field-components measured along the tunnel at 300 Hz, 750 Hz and 900 Hz.

Previously K. Sato and H. Toki reported the results of their study on the relation between power supply output topology and wiring configuration on the conversion of normal mode noise and ripple into common mode for the case of synchrotron magnet supplies. In an ideal situation when the power supply cables and magnets can all be arranged symmetrically as shown in Fig. 3, they showed that the common mode and normal modes can be kept decoupled, and that a noise filter can be most effective. HIMAC (Heavy Ion Medical Accelerator in Chiba) successfully implemented their analysis in its design [2]. In practice, they recommend two principles for reducing common mode noise: It is crucial to have a symmetric cabling configuration with a neutral ground line running as a central line along with the paired power cables and also the ground line should be returned to the mid-potential point of the power supply as shown in Fig. 3. The first point, implementing a symmetrical cabling network has been adopted elsewhere before [3], but even so, many cable wiring plants have continued to be installed asymmetrically. Perhaps this compromise did not cause trouble when thyristor rectifier supplies were mainly used; there the common mode noise might not have been so critical. Sato and Toki predicted that in the age of IGBT/IEGT supplies suppression of common mode noise conversion would become essential.

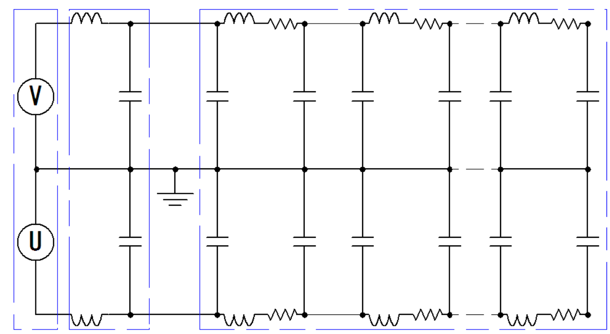


Figure 3: A symmetrical power supply and cabling configuration as described in ref. [2].

Returning to the MR, the power supply output circuit topology is not symmetrical and there is no mid-potential point where a ground line could be returned. To make matters worse, all of the magnets of the MR were wired in series forming a single loop around the tunnel.

Two identical current monitors are installed at the positive and negative output bus-bars of each power supply. It had been expected that the common mode current would be cancelled out by simple subtraction of these two current monitors. But as can be seen in Fig. (4-a), a large common mode ripple was apparent with the original unsymmetrical cabling making a complete circuit

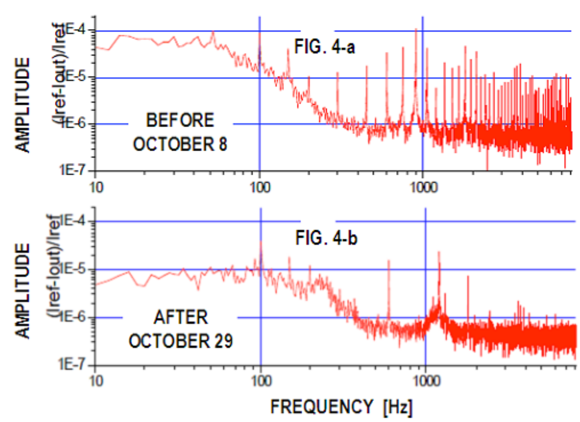


Figure 4: Subtraction of two current monitors. The original situation with unsymmetrical cabling (a). After the re-configuration of the cabling network (b).

around the tunnel.

To test if there might be a viable work-around solution to the problem, we decided to re-configure one of eleven Q-families. The one we chose for the experiment was comprised of only 6 magnets which we recabled symmetrically using three lines including a new ground line. After the re-configuration of the cabling network to be more symmetrical, the common mode noise disappeared from the subtraction of the two current monitor outputs (Fig. 4-b). This means that any common mode current out of the supply is now flowing with almost equal amplitude and phase.

There could be two ways to make the cabling network symmetric: One would be to connect the two upper coils N-S of each magnet in series on the outbound loop and the lower two S-N coils on the return; the alternative (which we eventually adopted) would be other to connect both N-N poles of each magnet on the outbound and S-S poles on the return. Simulations were done of each these alternative configurations. An unacceptable dipole-like component is generated by the common mode current in the former case pairing upper and lower coils. In the latter case where the N-N, S-S poles were paired symmetrically as shown in Fig 5, the quadrupole component excited by the common mode current is drastically reduced, however, at the expense of exciting slightly more octupole components. Therefore, we decided on the symmetric connection of Fig. 5. Apparently in the case of the original configuration, which made one grand series loop, both the normal and common mode currents generated quadrupole components proportional to the respective mode current. Figure 6 shows the before and after improvement of the quadrupole component measured at 900 Hz for a typical common mode. The improvement is obvious. This confirmed for us the hoped for drastic reduction of the quadrupole component

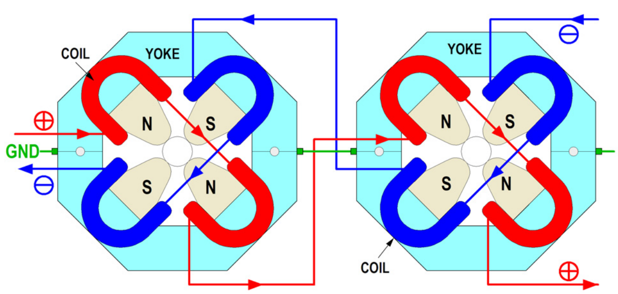


Figure 5: Quadrupole magnet connections. Like polarity poles are series connected.

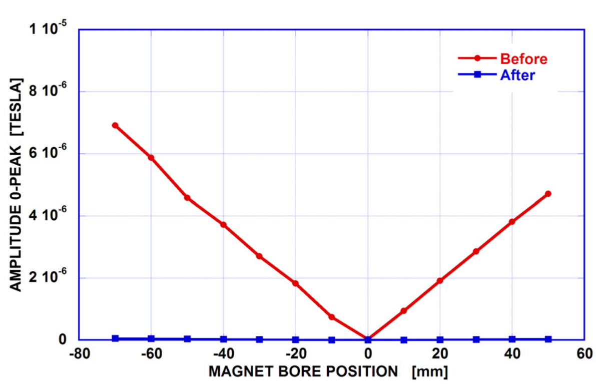


Figure 6: Quadrupole field-components measured at 900 Hz (common mode frequency). Plots are from before and after cabling re-configuration.

induced by common mode currents, and that the side effects of the re-configuration were negligibly small. Given this good result, we undertook to rewire all eleven networks for the 216 quadrupoles. Of course a symmetric cabling arrangement requires more expensive copper cable and labor to install, which is why an unsymmetrical grand series loop network had been chosen originally.

The 96 dipoles of the MR were already cabled with three lines including a ground line. However, the six power supplies driving the 96 dipoles were connected in an unsymmetrical series network. Therefore, we decided to divide the dipoles into six independent groups, and to symmetrize the networks. Use of a modern digital control system enabled the six independent power supplies to track each other very closely thus resulting in fairly small orbital fluctuation.

Experimental measurements show the improvement in beam parameters coming from the symmetrization efforts. Tune fluctuation before and after the wiring re-configuration is shown in Figures. 7-a and 7-b from June and December which compare the vertical tune fluctuation when operating in the 3 GeV storage mode. Tune fluctuation has been reduced by about one order of magnitude after the wiring network improvements.

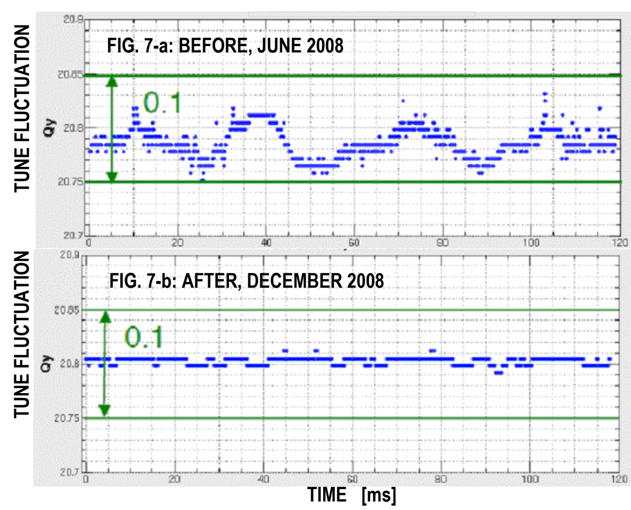


Figure 7: Tune fluctuation before (upper) and after the wiring re-configuration (lower) are shown.

BEAM ACCELERATION AND RESULTS

Through the early stages of beam commissioning, a very low beam current and a low repetition rate were used in order to minimize the radioactivation of accelerator components. The beam intensity of the RCS was 4×10^{11} protons per bunch (ppb), which corresponded to only 1% of the peak intensity of the design nominal power.

Fig. 8 shows a schematic view of the injection and collimator section. Beam injection into the MR uses the injection septum magnets 1 and 2, the injection kickers, and injection error was corrected with the vertical steering magnets in the 3-50 BT line. All the BPMs were used in the turn-by-turn mode for monitoring the betatron motion

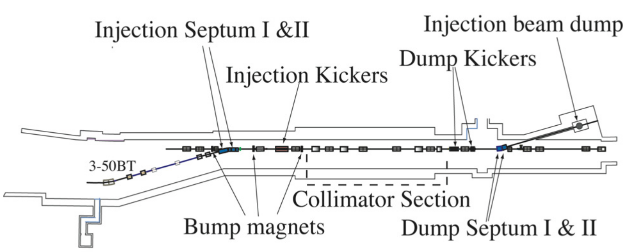


Figure 8: Layout of the injection and collimator section.

of the first several tens of turns just after the beam injection. The field strength of the dipoles was also adjusted to match the injection beam momentum.

Mountain-range plots of the vertical profile measured by the residual gas ionization profile monitor (IPM) are shown in Fig. 9(a) and (b) which correspond to before and after injection error correction, respectively. The beam emittance was estimated to be ~14πmmmrad.

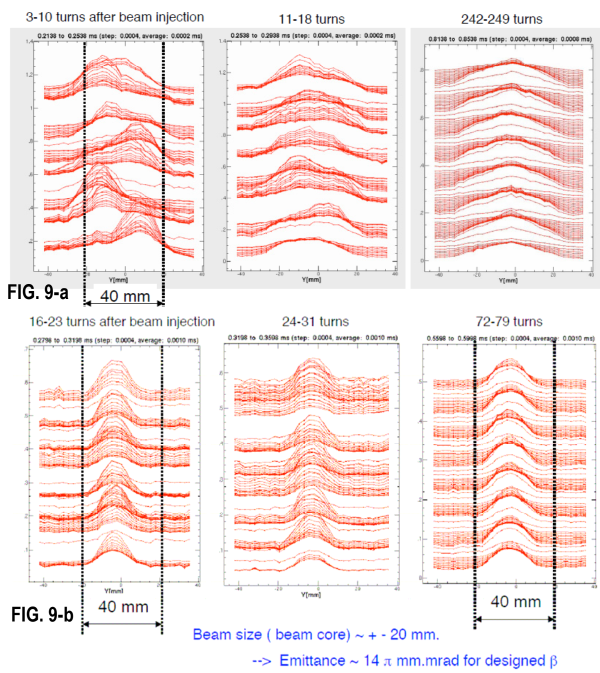


Figure 9: Mountain-range plots of the vertical profile measured by the residual gas ionization profile monitor (IPM). The upper traces measure when there was injection mismatch; the lower traces show after matching correction. Each figure shows transverse beam profiles progressing from early turns (left) to latter ones (right).

Matching between the magnetic field strength of the dipole magnets and the rf frequency was performed using a wall current monitor. Beam acceleration was successfully performed on the 23rd of December 2008. Figure 10 shows beam current during acceleration, and mountain-range plots of the longitudinal beam profile during acceleration are shown in Fig. 11. No beam loss was observed during acceleration. As described before, the MR has an imaginary transition energy, which seems to contribute to this smooth acceleration.

Figure 12 shows the dispersion functions measured at one of the three arcs. The dp/p dependence of the closed orbit was measured by changing the rf frequency after beam injection. The measured results agree well with the design value. Chromaticity is well corrected to almost zero. The transverse beam emittance during acceleration was adiabatically damped in this small current region as shown in Fig. 13.

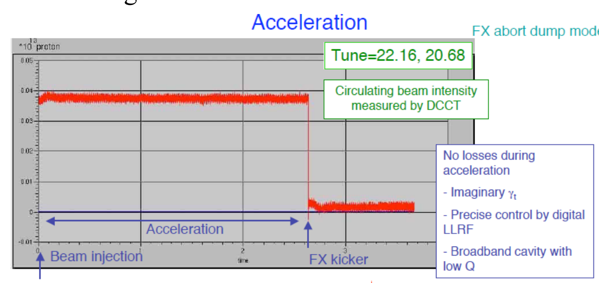


Figure 10: Beam current during acceleration. Acceleration time was 2.5 sec, then beam was extracted by the fast extraction system.

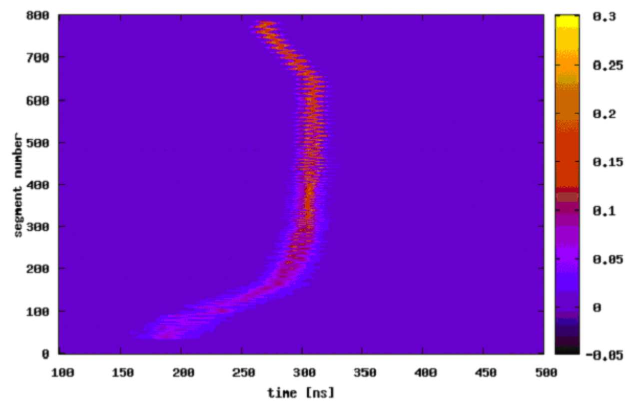


Figure 11: Longitudinal beam profile during acceleration. Vertical: acceleration time from 0 to 2.5 sec. Horizontal: relative phase between beam and accelerating microwave (full width 500 nsec).

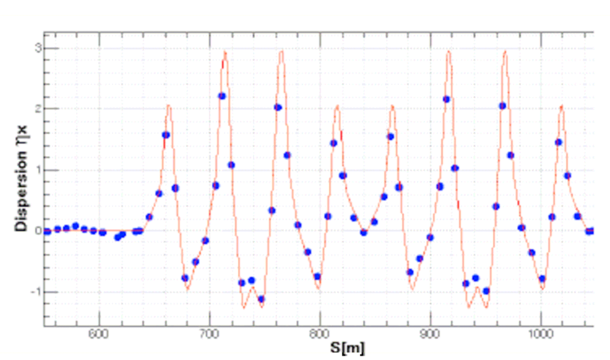


Figure 12: Measured dispersion (blue dots) shown with the design calculated plot (red line).

EXTRACTION OF THE BEAM

There are two extraction sections in the MR. On is the fast extraction for neutrino experiments and the other is a slow extraction for hadron experiments. The fast extraction system of the MR is bi-polar so that the extracted beams can be directed either to the neutrino

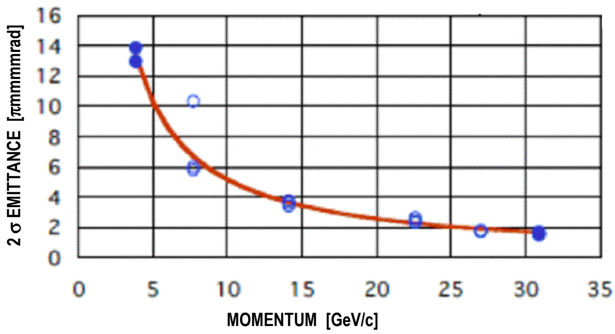
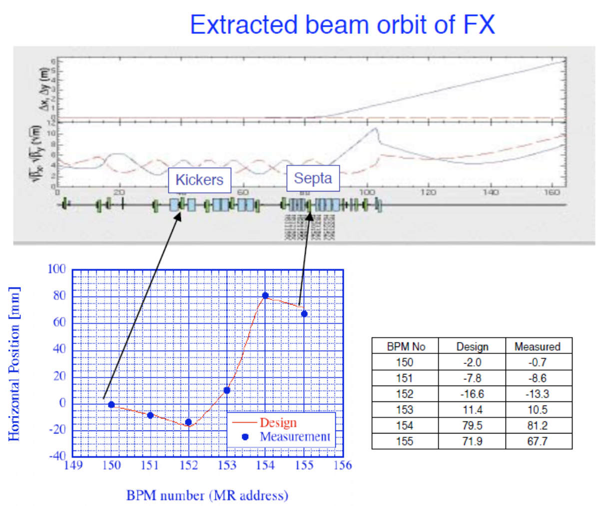


Figure 13: Measured beam emittance from 3 GeV to 30 GeV (circles). The line shows emittance as a function of beam momentum.

beam line or an abort beam dump depending on the polarity of the kicker magnets. Fig. 14 (upper) shows the configuration for fast beam extraction. The measured orbit for the fast extraction agrees well with designed as shown in Fig. 14. In this beam commissioning, the beam was extracted only to the beam abort line as the construction of the neutrino line was still underway. In May 2009, beam will be extracted into the neutrino beam line.



BPM No	Design	Measured
150	-2.0	-0.7
151	-7.8	-8.6
152	-16.6	-13.3
153	11.4	10.5
154	79.5	81.2
155	71.9	67.7

Figure 14: Schematic view of the fast extraction section (upper). Horizontal beam position along extraction section (lower): measured (dots) and designed (line).

Slow extraction was carried out in January 2009. Only a day of beam commissioning was needed to enable us to extract beams using the slow extraction devices. The output has a spike-like time structure (Fig. 15). A feedback system for slow extraction, will be installed in summer shutdown of 2009. A feed forward system to reduce 50-100 Hz current ripple from the power supplies is now under investigation.

SUMMARY

First stage beam commissioning of the MR was carried out in May and June 2008. At that time, large common

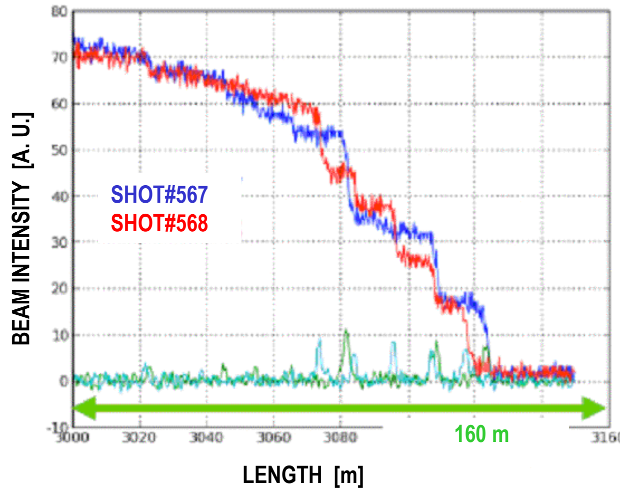


Figure 15: Beam current during extraction. The two decaying lines record the stored current in the MR for two arbitrary shots. Corresponding impulsive extracted beam currents are shown in the bottom trace.

mode current ripple causing both orbit and tune fluctuation was discovered. By recabling the magnet supply network to be more symmetric, orbit and tune fluctuations were reduced to an acceptable range for the first stage of machine commissioning. Discussions into the possibilities for reconfiguration of the power supply output topology began in preparation for when further stability for high current acceleration will be needed.

Beam acceleration was very smoothly performed with no beam loss. The current accelerated was about 1% of the full current. Performance at higher currents will be studied later. Extraction systems both for fast and slow beams worked well. The MR aims very high power and all studies for that have just begun.

ACKNOWLEDGEMENT

This report presents a summary of the work done by the staff of the J-PARC MR group. Much of the work reported here has been described in greater detail over the past years at conferences and can easily be accessed through the JACow web page at: http://www.jacow.org/

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