BEAM DYNAMICS SIMULATIONS OF J-PARC MAIN RING FOR DAMEGE RECOVERY FROM THE TOHOKU EARTHQUAKE IN JAPAN AND UPGRADE PLAN OF FAST EXTRACTION OPERATION

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Abstract

Magnets of Japan Proton Accelerator Research Complex (J-PARC) were shaken by the Tohoku Earthquake in Japan on March 11th, 2011. The alignment of J-PARC Main Ring (MR) received 20 mm displacement horizontally and 6 mm vertically. Beam dynamics simulations were performed to estimate the effect of the displacement on closed orbit distortions and beam loss in fast extraction (FX) operation of J-PARC MR. Based on the simulation results, we concluded that re-alignment of J-PARC MR was needed to achieve high-power beam. The re-alignment of MR was finished on October 28th, 2011. We also considered the effects of the earthquake on the upstream of MR to establish our upgrade plan, which was based on beam dynamics simulations optimizing collimator balance of injection beam transport (3-50BT) and MR, and RF patterns. J-PARC MR FX operation was resumed from December 2011.

DISPACEMENT OF ALIGNMENT AND CLOSED ORBIT DISTORTION IN MAIN RING

Displacement of MR alignment right after the Tohoku earthquake was measured in last June [1]. We simulated the bare and corrected closed orbit distortion (COD) by SAD code [2] with August 2010 alignment and June 2011 alignment each [3]. MR was re-aligned in October 2011, but we assume that October 2011 alignment is same as August 2010 alignment in this paper. Table 1 shows that simulated rms bare COD and rms corrected COD for August 2010 alignment and June 2011 alignment in MR. Even with steerer correction the displacement of alignment would move COD. Table 2 shows that measured rms bare COD and rms corrected COD in February 2011 and December 2011. Figure 1, 2, and 3 show the bare COD simulated with August 2010 alignment, bare COD measured on 02/25/2011, and bare COD measured on 12/22/2011. These COD sets, except for the ones simulated with June 2011 alignment, show almost same size horizontally and vertically. It supports our assumption to discuss MR beam loss in next section.

Table 1: Simulated rms COD in MR

Alignment	rms bare CODX	rms bare CODY	rms corr. CODX	rms corr. CODY
Aug. 2010	2.71 mm	1.50 mm	0.22 mm	0.19 mm
Jun. 2011	5.71 mm	8.35 mm	0.42 mm	0.37 mm

Table 2: Measured rms COD in MR

Alignment	rms bare CODX	rms bare CODY	rms corr. CODX	rms corr. CODY
Feb. 2011	~2.0 mm	~2.0 mm	0.8 mm	0.4 mm
Dec. 2011	~2.0 mm	~1.8 mm	0.8 mm	0.4 mm

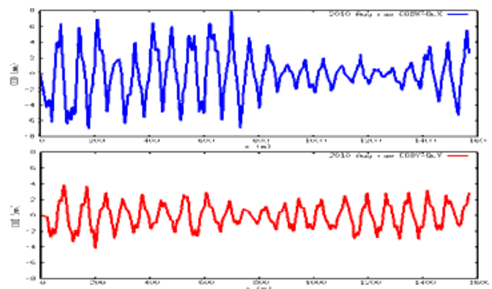

Figure 1: Simulated bare COD in horizontal (upper) and vertical (lower) directions with August 2010 magnetic alignment in MR. Horizontal axis is MR longitudinal position.

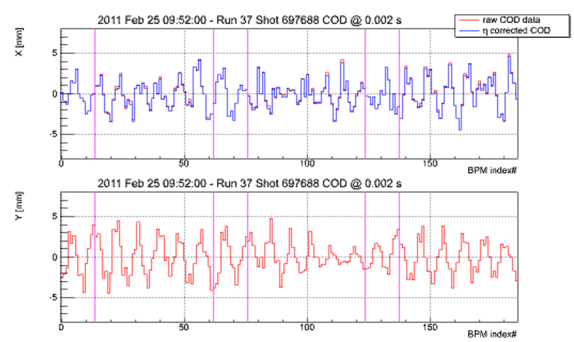

Figure 2: Measured bare COD in horizontal (upper) and vertical (lower) on 02/25/2011 right before the Tohoku earthquake. Horizontal axis is MR BPM index.

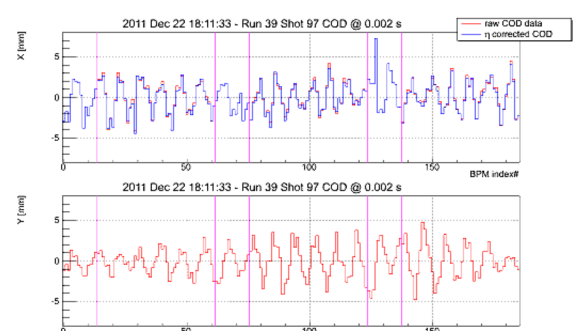

Figure 3: Measured bare COD in horizontal (upper) and vertical (lower) on 12/22/2011 after the Tohoku earthquake and realignment. Horizontal axis is MR BPM index.

ALIGNMENT EFFECT IN MR 190 KW AND 250 KW OPERATIONS

Effect of displacement of alignment is also shown in beam loss simulations with corrected COD. These simulations were needed to determine our maintenance schedule, especially to find out realignment effects before long shut down in 2013, when linac system is to be upgraded from 181 MeV to 400 MeV. In this section, we discuss MR 190 kW and 250 kW operations for different beam power form upstream 3 GeV Rapid Cycle Synchrotron (RCS) (Table 3).

Our simulation process of MR is almost same as in our basic upgrade planning [3]. Between H- ion source and MR there are 181 MeV linac, 3 GeV RCS, and beam transport from RCS to MR (3-50BT). RCS is simulated with SIMPSONS [4,5]. 3-50BT is simulated with SAD. MR is simulated with SAD and SCTR [6]. These simulations include magnetic field errors and alignment errors, but does not include kick from reflected pulse of Injection kicker, magnet ripple during smoothing acceleration, nor beam loading effects for MR (Table 4). RF pattern and tune setting are optimized as in Ref. [3]. In actual operation of MR, there are large beam losses at injection kicker timings, and needed RF voltage is higher than simulated value because the beam loading effect is not compensated yet. Therefore direct comparison between simulation and experiment is difficult for high intensity beam to discuss optimal RF pattern.

Table 3: MR Conditions in Simulations

190 kW operation Before Summer 2012	250 kW operation Before Summer 2013
Repetition time 2.56 s Injection 0.12 s Acceleration 1.4 s Smoothing 0.1 s Alignment of RCS: 2010 (realignment) 2011 (no-realignment)	Tune: H 22.41, V 20.76 350 BT collimator 54 pi MR collimator 60 pi Alignment of MR: Aug. 2010 (realignment) Jun. 2011 (no-realignment)
Linac 15 mA RCS 300 kW MR RF h=9 only	Linac 20 mA RCS 400 kW MR RF h=9 and h=18

Table 4: Errors of RCS and MR in Simulations

RCS	MR
Field & Alignment Errors Nonlinear fields of ring magnets Leakage field from Extraction line Edge focus of injection bump magnets COD correction	Field & Alignment Errors Nonlinear fields of ring magnets Leakage field from injection septum magnet I COD correction

MR 190 kW Operation

MR beam loss simulations under MR 190 kW operation tell that MR realignment, to be similar to MR August 2010 alignment, can reduce beam loss whether RCS is realigned or not (Figures 4-5, Tables 5). 350BT losses were measured both before and after the Tohoku earthquake [7], but the latter is much smaller than our simulation, even though RCS is not realigned after the Tohoku earthquake. Therefore, actual beam quality from RCS is much better than our simulation. The reason is under study now. Recently RCS operation is upgraded from these simulation conditions [8]. In May 2012 MR achieved 190 kW user operation.

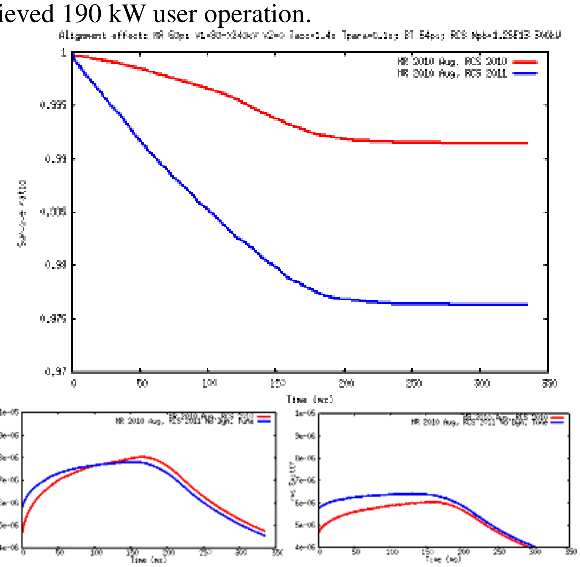

Figure 4: Simulated MR beam dynamics with MR August 2010 alignment in MR 190 kW operation. Horizontal axis is time from injection to end of smoothing acceleration. Red line is for RCS 2010 alignment, blue line is for RCS summer 2011 alignment. Each vertical axis is MR survival ratio from 1 to 0.97 for upper figure, rms horizontal emittance from 4 to 10 mm mrad for down-left figure, and rms vertical emittance from 4 to 10 mm mrad for down-right figure.

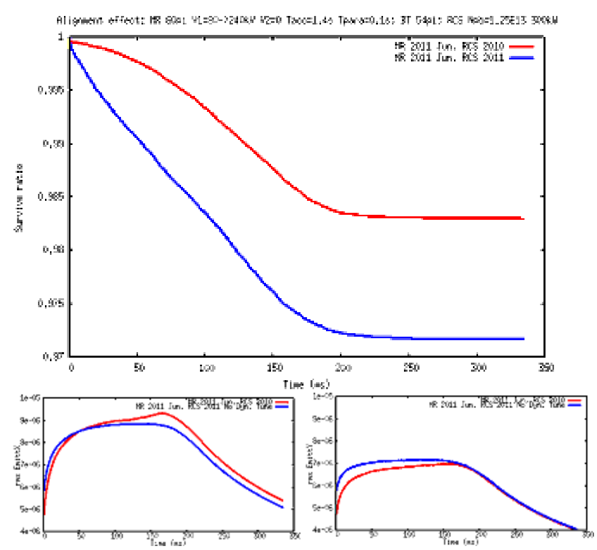

Figure 5. Simulated MR beam dynamics with MR June 2011 alignment in MR 190 kW operation. Horizontal axis is time from injection to end of smoothing acceleration. Red line is for RCS 2010 alignment, blue line is for RCS summer 2011 alignment. Each vertical axis is MR

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survival ratio from 1 to 0.97 for upper figure, rms horizontal emittance from 4 to 10 mm mrad for down-left figure, and rms vertical emittance from 4 to 10 mm mrad for down-right figure.

Table 5: Simulated Loss in MR 190 kW Operation

	350 BT	MR realigned	MR not realigned
RCS realigned (Feb. 2011 meas.)	40 W (~40 W)	120 W	230 W
RCS not realigned (Dec. 2011 meas.)	560 W (~70 W)	310 W	380 W

MR 250 kW Operation

MR 250 kW operation is also discussed. In MR operation only fundamental RFs have been used, but second harmonic RFs are going to be used to increase bunching factor and reduce space charge effect from winter 2012. Beam dynamics simulations are performed under MR realigned MR but RCS with and without realignment (Figures 6.7, and Table 6). Only from the simulation results, MR 250 kW operation without RCS realignment causes severe beam loss. However, as already mentioned in previous subsection, this loss may be over estimated.

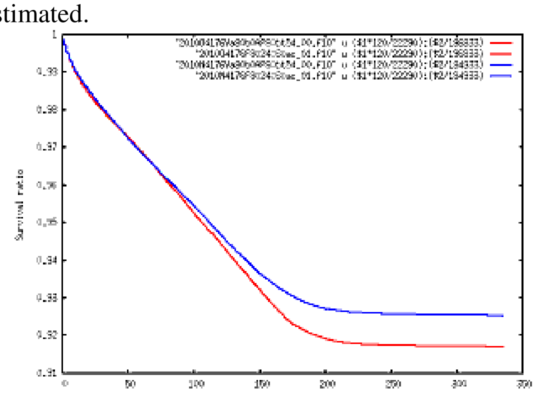

Figure 6: Simulated MR beam loss in MR 250 kW operation with MR RF h=9 only and MR August 2010 alignment. Horizontal axis is time from injection to end of smoothing acceleration. Vertical axis is MR survival ratio from 1 to 0.97. Red line is for RCS 2010 alignment, blue line is for RCS summer 2011 alignment.

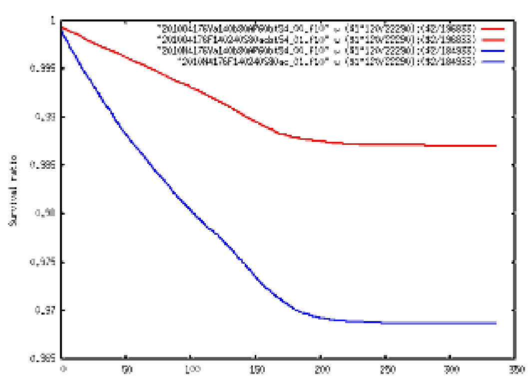

Figure 7: Simulated MR beam loss in MR 250 kW operation with MR RF h=9 & h=18 and MR August 2010 alignment. Horizontal axis is time from injection to end of smoothing acceleration. Vertical axis is MR survival ratio from 1 to 0.97. Red line is for RCS 2010 alignment, blue line is for RCS summer 2011 alignment.

Table 6: Simulated Loss in MR 250 kW Operation

	350 BT	MR realigned RF h=9	MR realigned RF h=9, 18
RCS realigned	260 W	500 W	240 W
RCS not realigned	1.5 kW	1.3 kW	520 W

CONCLUSIONS

- We have performed beam loss simulation in J-PARC MR to estimate the effect of magnet displacement and to discuss necessity of re-alignment after the Tohoku Earthquake.
- The displacement causes not only larger bare COD but also larger corrected COD. We found that even with corrected COD the increased beam loss is not negligible.
- We assumed that the realigned geometry is the same of the alignment data measured in August 2010 for MR, and 2010 for RCS. No-realigned geometries are measured in 2011 summer for both MR and RCS. Through beam dynamics simulation, we can say that each of MR and RCS alignment affects on MR beam loss. From maintenance schedule we have to operate RCS without realignment till 2013 summer. However, realignment of MR reduces beam loss and helps to achieve high-power beam.

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