BEAM DYNAMICS SIMULATIONS OF J-PARC MAIN RING FOR UPGRADE PLAN OF FAST EXTRACTION OPERATION

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Abstract

Beam loss simulations were performed in order to establish our upgrade plan of high intensity proton beams in fast extraction operation of Japan Proton Accelerator Research Complex (J-PARC) Main Ring (MR). It is especially important to keep beam loss within the collimator capacity of accelerators for a J-PARC radio-activation control scenario. To evaluate our procedure of simulations, we compared the simulated beam losses with the beam losses measured in our past operations with DC Current Transformer (DCCT). To upgrade beam power, increasing protons per bunch and making higher repetition pattern are considered. Through simulations including space charge effects, we found that to optimize both 2nd RF voltage pattern and phase pattern is a strong key to reduce beam losses for higher repetition. Upgrade scenarios of different repetition times are presented.

COMPARISON BETWEEN SIMULATION AND MEASURED BEAM LOSS SIMULATION BENCHMARK

Our simulation process of MR is as follows. Between H- ion source and MR there are 181 MeV (400 MeV in 2013) linac, 3 GeV Rapid Cycle Synchrotron (RCS), and beam transport from RCS to MR (3-50BT). RCS is simulated with SIMPSONS [1,2]. 3-50BT is simulated with STRUCT [3] and SAD [4] separately. MR is simulated with SAD and SCTR [5].

We compared beam loss time structure between simulation and measured data by DCCT on Feb. 14th, 2011 (Fig. 1). The measurement was performed in Fast Extraction (FX) operation. In the FX operation 2 proton bunches were produced from RCS every 40 ms. Each bunch had about 1.2E13 protons. They were injected into MR 4 times in 120 ms. Totally 8 bunches were injected, accelerated from 3 GeV to 30 GeV, and extracted as a pulse every 3.2 s. The 1st injection timing was called K1. The 1st RF voltage, V1, was kept 80 kV during the 120 ms injection time. After injection time V1 was varied to 190 kV linearly from K1+120 ms to K1+270 ms. The acceleration time was 1.9 s starting from K1+150 ms. It consisted of 0.1 s smoothing, 1.7 s linear acceleration, and 0.1 s smoothing. Most beam losses happened during the injection time and first smoothing time. To analyze time structure of beam loss carefully, we injected only 2 bunches into MR in Fig. 1. In Fig. 1 the time structure of survival protons show similar pattern between simulation and measurement. The difference of beam loss ratio was within 30 %. Therefore we decided to adopt this simulation procedure to establish our upgrade plan. After the East-Japan Earthquake on Mar. 11, 2011, whole alignments of magnets in J-PARC were moved. Figures 2 show the COD comparison calculated by SAD with August 2010 alignment and Jun 2011 alignment in MR. J-PARC new alignment is under taking. The effect on beam loss is under calculation.

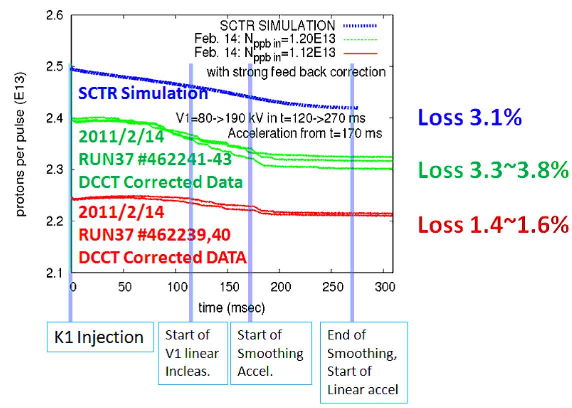

Figure 1. Beam survival time structure in MR FX operation. Blue line is 2.5D simulation (with SCTR code) result. Green lines are experimental results corresponding MR 145 kW FX operation. Red lines are experimental results corresponding MR 133 kW FX operation. Same color lines mean different shots under the same condition.

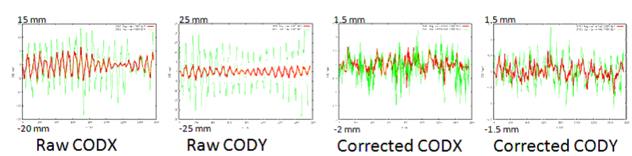

Figure 2. Raw COD and COD corrected by steerers. Red lines are with August 2010 magnetic alignment, and Green lines are with Jun 2011 magnetic alignment. Horizontal axis is MR longitudinal position.

J-PARC MR UPGRADE STRATEGY FOR 750 KW FX OPEARTION

The collimator capacity of MR was 450 W, but it is upgraded till 2 kW. For 3-50BT it is 2 kW. It is important for MR upgrade to keep the beam losses within the capacities. Our upgrade plan is based on increasing protons per bunch and making higher repetition pattern. More protons per bunch cause larger beam loss exponentially because of their space charge effect. Higher repetition increases beam loss linearly. However, high repetition time is limited by power supplies of electric magnets. Therefore, we need to balance number of protons per bunch and repetition time by using simulation results. Parameters to be optimized are RCS

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injection/extraction condition, collimator size of 3-50BT and MR, tune, MR RF voltage and phase pattern.

Figs. 3 show beam losses for repetition time 1.28 s at 3-50BT (left figure), and at MR during injection time (right figure). Collimator jaws are set 54pi mm mrad at 3-50BT, and 65pi mm mrad at MR. Capacities of both collimators are 2 kW. MR beam loss during injection time is about 3/4 of total MR beam loss. This ratio varies depending of RF patterns and other conditions, but it is that order as a whole. Full errors of RCS and MR mean as in Table 1. Figs. 3 tell that exponential increasing of beam losses for higher protons per bunch. Even with idealistic RCS condition, MR FX operation can accept ~700 kW from RCS. For realistic condition MR FX operation can accept 500~600 kW from RCS. Certainly the acceptable power depends on repetition time and collimator balance of 3-50BT and MR.

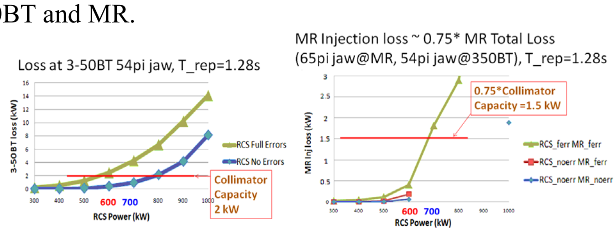

Fig. 3. Beam loss at 3-50BT and MR injection time.

Table 1: Errors of RCS and MR.

RCS Full Errors: Field & Alignment Errors Nonlinear fields of ring magnets Leakage field from Extraction line Edge focus of injection bump magnets COD correction	MR Full Errors: Field & Alignment Errors Nonlinear fields of ring magnets Leakage field from Injection Septum Magnet I (Not Septum II) COD correction
RCS No Error: Nonlinear fields only	MR No Error: None of above lists

RF OPTIMIZATION PROCESS

This section concentrates on RF pattern to control beam loss. MR is going to have main RF and 2nd harmonic RF.

Main RF voltage optimization

From longitudinal simulation (1D), increasing top of main RF voltage (V1_top) reduce whole beam loss. However from SCTR simulation (2.5 D) including transverse space charge effect, there is an optimal voltage for V1_top. Figure 4 shows the comparison between 1D results and 2.5D results. Figure 5 shows time structure of survival beam ratio with 2.5D simulation. RCS conditions are no error, 600 kW, 400 MeV centered injection. MR conditions are full errors, total acceleration time 0.5 s, smoothing time 0.1 s, and repetition time 1.28 s. V1 is 140 kV during injection. 2nd RF Voltage (V2) during injection is 91 kV for 2.5D simulation and 95 kV for 1D simulation. V2 goes to 0 linearly at the end of 1st smoothing acceleration. With 2.5D simulation optimal V1_top is 440 kV. This result shows that 2.5D simulation is necessary to determine V1_top.

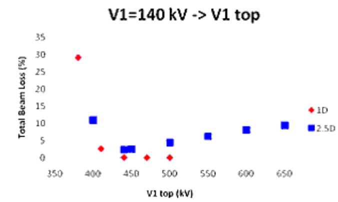

Figure 4. Beam loss ratio depending on top voltage of main RF, V1_top. Red marks are 1D simulation results. Blue marks are 2.5D simulation results including transverse space charge effect.

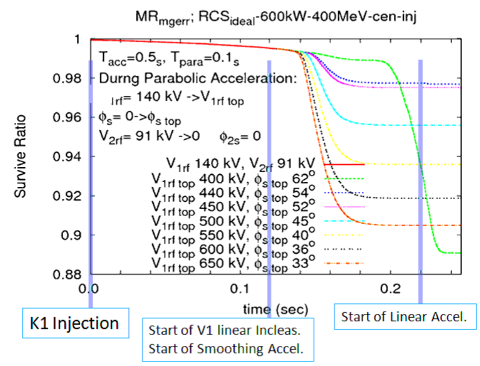

Figure 5. 2.5D simulation results of survival ratio of a proton bunch injected at 1st injection timing with changing top voltage of main RF.

2nd RF optimization

We still have a key to control beam loss in 2nd harmonic RF. Synchrotron equation of motion of double RF system is described as follows,

$$\frac{d}{dt}\left(\frac{\Delta p}{p}\right) \propto \begin{bmatrix} V_1\{\sin(\phi)-\sin(\phi_{1s})\} \\ -V_2\{\sin 2(\phi-\phi_{1s}-\phi_{2s})-\sin 2(-\phi_{2s})\} \end{bmatrix} \quad (1)$$

, where p is momentum, V_1 is main RF voltage, V_2 is 2nd harmonic RF voltageφ_1s is the phase of synchronous particle, φ_2s is corresponding phase of 2nd RF. From 2.5D simulation just changing V_2 is not effective to reduce beam loss. However introducing a pattern to φ_2s can reduce beam loss, even though φ_2s had been kept 0 normally. The purpose to use φ_2s > 0 is to modify RF bucket during 1st smoothing acceleration and increasing bunching factor to reduce space charge effect. Theoretical model by Kats ans Weng [6] tells that φ_2s >0 mitigates space charge effect for 0.25< V2/V1 < 0.5. However, our 2.5 D simulations tell that it works even for V2/V1 > 0.5. Figure 6 shows the effect of using φ_2s >0 pattern on beam survival ratio. Conditions are same as V1_top=440 kV case in Fig. 4 except for φ_2s >0 pattern. During 0.1 s smoothing time the pattern varies φ_2s from 0 to an end value, φ_2s_end, linearly. At the end of the smoothing time there is no effective acceleration voltage from 2nd RF, because V2 reaches 0 though φ_2s > 0. The optimal φ_2s pattern was searched by changing the φ_2s_end. For MR

730 kW operation, optimal φ_2s > 0 pattern provides total MR loss 0.5 kW with 65pi mm mrad jaw, while φ_2s =0 provides total MR loss 1.5 kW.

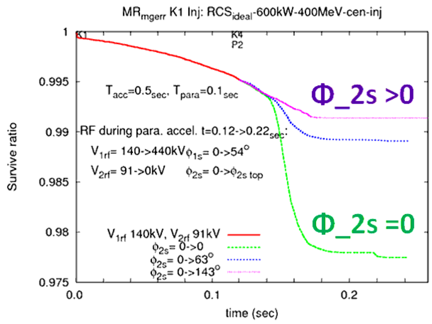

Figure 6. Effect of φ_2s >0 pattern on beam survival ratio. Conditions are the same as V1_top=440 kV case in Fig. 5 except for φ_2s pattern. Green line is for φ_2s =0, and it is the same as blue line in Fig. 5.

UPGRADE SCENARIO

Previous section was under idealistic conditions for RCS. To establish our upgrade scenario, we considered full error case for both RCS and MR. Repetition time was chosen 1.28 s for newly proposed power supply under development, and 2.4 s for current power supply.

With new power supply (under development)

Power supply team of KEK/J-PARC is developing new power supply system. If it is successfully developed, we can expect 1 Hz repetition in MR FX operation. Figure 7 shows survival ratio in MR under RCS: full error, 600 kW, 400 MeV centered injection, and MR: full error, repetition time 1.28 s, acceleration time 0.5 s, smoothing time 0.1 s. MR conditions are same as in Fig. 6. For this case our scenario is MR 724 kW, 3-50 BT loss 1.7 kW at 57pi mm mrad jaw, MR total loss 0.9 kW at 65pi mm mrad jaw under repetition time 1.28 s.

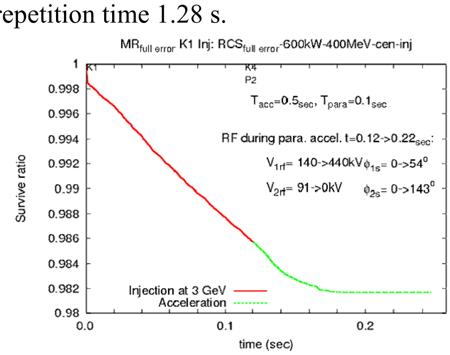

Figure 7. Survival ratio of power upgrade scenario with new power supply.

With current power supply

Current power supplies are also upgraded. In early 2011 the repetition time was 3.2 s, but it is going to be 2.4 s next year. Figure 8 shows survival ratio in MR under RCS: full error, 700 kW, 400 MeV centered injection, and MR: full error, repetition time 2.4 s, acceleration time 1.2 s, smoothing time 0.1 s. V1=140 kV, V2=91 kV during injection. V1_top is 240 kV, which is along with our RF upgrade plan next year. V2 at the end of smoothing time is 0 or 10 kV. This difference is small on survival ratio, but to reach complete 0 is hard problem. This result shows that RF group do not need to get complete 0 of V2. For this case our scenario is MR 435 kW, 3-50 BT loss 1.3 kW at 60pi mm mrad jaw, MR total loss 1.3 kW at 65pi mm mrad jaw under repetition time 2.4 s.

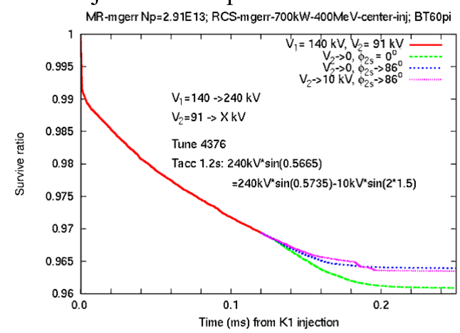

Figure 8. Survival ratio of power upgrade scenario with current power supply. Green line is for V2=91 kV to 0 during smoothing and φ_2s=0, blue line is for V2=91 kV to 0 and φ_2s=0 to 86 degree during smoothing, and purple line is for V2=91 kV to 10 kV and φ_2s=0 to 86 degree during smoothing.

CONCLUSIONS

- Beam dynamics 2.5D simulations were performed for J-PARC MR FX operations. By comparison of the time structure of beam survival amount to experimental results, the simulation procedure was benchmarked.
- MR upgrade strategy is basically increasing protons per bunch and higher repetition. By 2.5D simulation the acceptable beam power from RCS is around 600 kW to 700 kW for MR FX operation.
- RF optimization process is to optimize top voltage of main RF, and to optimize phase of 2nd RF pattern. The optimal values depend on acceleration time.
- Upgrade scenarios were established. We may get MR 724 kW with new power supply and repetition time 1.28 s, and MR 435 kW with current power supply and repetition time 2.4 s.

REFERENCES

[1] S. Machida, SSCL-PREPRINT-197 (1993).
[2] H. Hotchi et al., Proceedings of IPAC10, 624 (2010).
[3] A. Drozhdin and N. Mokhov. The STRUCT program user's reference manual. http://www-ap.fnal.gov/drozhdin.
[4] K. Oide et al., http://acc-physics.kek.jp/SAD/.
[5] K. Ohmi et al., Proceedings of PAC07, 3318 (2007).
[6] J. M. Kats and W. T. Weng, Proc. XVth Int. Conf. on High Enerty Accelerators, Hamburg, July 20-24 1992, p.1052