# COHERENT OSCILLATION SIMULATIONS OF BEAM INSTABILITY GENERATED DURING DEBUNCHING FOR J-PARC SLOW EXTRACTION

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*Abstract*

The J-PARC Main Ring (MR) has achieved a high extraction efficiency above 99.6% during 30 GeV slow extraction at the current beam power of 95 kW ($8.4 \times 10^{13}$ ppp). We have observed ring-wide beam loss due to transverse beam instability associated with vacuum pressure rise and electron cloud, believed to be triggered by longitudinal microwave structure in the beam. To achieve stable operation, we have implemented novel RF manipulations at the injection and for the debunching. The generation of the longitudinal microwave structure and coherent transverse oscillation by the electron cloud during debunching has been investigated using newly developed simulation codes.

## INTRODUCTION

The J-PARC Main Ring (MR) has achieved a high extraction efficiency above 99.6% during 30 GeV slow extraction at the current beam power of 95 kW ($8.4 \times 10^{13}$ ppp). However, at beam powers above 30 kW, we observed ring-wide beam loss due to transverse beam instability associated with vacuum pressure rise and electron cloud (EC), believed to be triggered by longitudinal microwave structure in the beam [1]. To achieve stable operation, we implemented phase offset injection into RF buckets [1] and a two-step RF voltage reduction technique for debunching, in addition to chromaticity control [2]. The longitudinal microwave structure generation by the longitudinal impedances [3], electron cloud generation, and coherent transverse oscillation by the electron cloud during debunching have been investigated using newly developed simulation codes. The codes model the electron cloud–beam interaction as a transverse wake (impedance) derived from an EC oscillation defined by neutralization factor and EC-beam distributions. Through this study, we will explore further instability mitigation strategies toward higher beam intensity operations planned for the future.

## BEAM INSTABILITY AND MITIGATIONS

The beam debunching for slow extraction was originally conducted by turning off the RF voltage at the flat-top start timing P3 called 1-step debunch, which is shown in Fig. 1 left. The RF voltage during a linear acceleration is set to 400 kV at 4.24 s cycle and adiabatically reduced to 256 kV during 0.1 s parabolic acceleration to a flat top to suppress the beam wake in the RF cavities during debunching. A new

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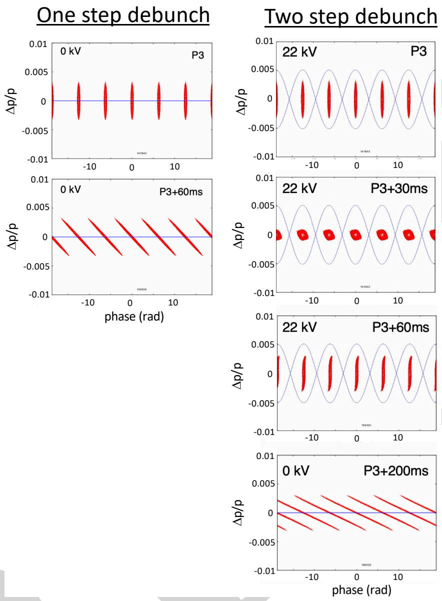


Figure 1: Beam distributions by two debunching manipulations.

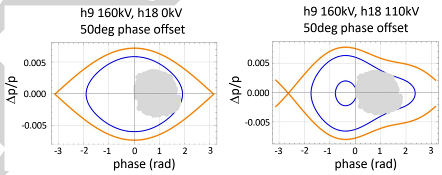


Figure 2: Separatrices and injected beam w/o and w/ 2nd harmonic RF.

RF manipulation technique called 2-step debunching was introduced [2] (see Fig. 1 right). The RF voltage was non-adiabatically reduced from 256 kV to 22 kV and turned off after a half synchrotron period (~60 ms). On the other hand, in order to enlarge the longitudinal beam emittance, 3 GeV beam from the RCS was injected into the MR fundamental RF buckets with a phase offset of typically ~50 deg as shown in Fig. 2 left [1]. In April 2025, a 110 kV second harmonic RF system was implemented with the 160 kV fundamental RF during the flat bottom energy [4]. As shown in Fig. 2 right, the beam is injected with a phase offset of ~50 deg for the fundamental RF bucket center. The second harmonic RF phase center is set at the same phase offset (~50 deg from fundamental RF phase center) [5]. This manipulation reduced the beam loss at the injection energy and the beginning of the acceleration by bunching factor improvement, and also suppressed the instability during debunching. The beam power has reached 92 kW (~$8 \times 10^{13}$ ppp) in physics

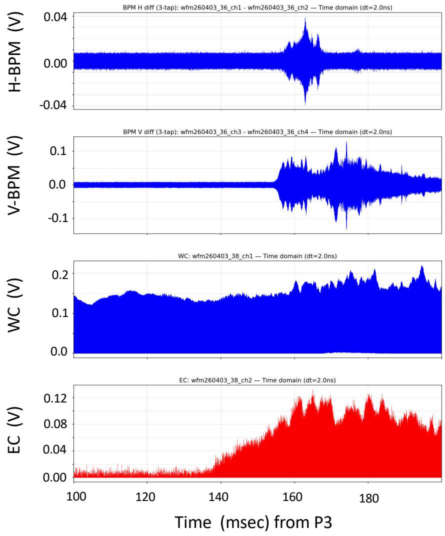


Figure 3: Coherent oscillation, WC and EC signals.

run. The turning off timing from 22 to 0 kV in the 2-step debunch was changed from 60 to 50 ms (P3 origin). The instability is significantly suppressed and the beam power rose up to 95 kW for physics run and to 100 kW for one hour target test run.

Figure 3 shows an example of the observed beam instability during debunching in the beam test. The beam power is 111 kW (~$9.8\times10^{13}$ ppp), the RF manipulation at the injection is that of Fig. 2 right. The 2-step debunching timing setting RF voltage zero is 60 ms from P3. The horizontal and vertical coherent oscillation amplitudes were obtained by removing the revolution harmonic components from the raw BPM signal. Clear horizontal and vertical coherent oscillations were seen in the range of 160 to 180 ms from P3, in which the electron cloud has a broad peak. The microwave structure in the wall current (WC) signal was observed as described in the next section. The ring-wide strong beam loss often observed in such conditions did not occur in this example.

## ELECTRON CLOUD SIMULATION

A new code has been developed to investigate the relation between the electron cloud build-up and the beam time structure in debunching for the J-PARC MR. The code is

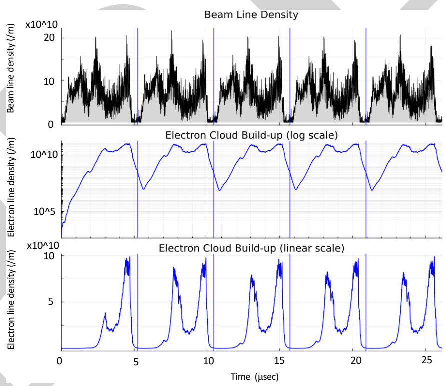


Figure 4: Measured beam and simulated EC line densities.

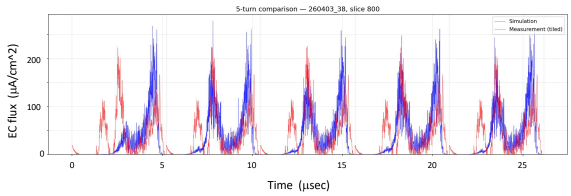


Figure 5: Measured and simulated electron flux.

written purely in Julia. The beam with fixed transverse distribution moves in the longitudinal direction. The electric fields of the beam and electron cloud in the vacuum chamber boundary are solved by a Particle-In-Cell (PIC) algorithm. Macro-electrons move under the electric fields of the beam and electron cloud. The Macro-electron number can be adjusted according to the simulated EC density. Figure 4 shows the measured beam line density at ~180 ms timing in Fig. 3 WC plot, and electron line density simulated over 5 turns. Residual gas ionization with 2 Mb cross section and vacuum pressure of $1\times10^{-8}$ Torr is given as an initial electron generation source. A circular vacuum chamber of 67 mm radius (field-free region) is assumed, matching that at the address-47 EC monitor location [6]. Main parameters describing the secondary electron yield, $\delta_{max}$, $E_{max}$ and $R_0$ are chosen to be 1.3, 390 eV, 0.40, so as to reproduce the measured electron flux pattern. We should note that the parameters are discrepant from those of the previous work using PyECLOUD code [7].

The electron cloud builds up rapidly, reaching ~ $1\times10^{11}$ within the first turn. The peak line density is expected to be limited by the electron space-charge force. Figure 5 shows the comparison between measured (red) and simulated (blue) electron flux. The simulated flux pattern roughly reproduces the measured one.

## LONGITUDINAL BEAM SIMULATION

The longitudinal intensity modulation during debunching was investigated using a 6D tracking simulation code (Fortran) that incorporates the beam coupling impedance. The transverse tracking simulation switch is turned off to save the computation time. Figure 6 shows the real part of summed coupling impedances normalized by revolution harmonics $n$. The RF system for SX operation consists of 8 fundamental, 2 2nd-harmonic, 2 fundamental gap-shorted spare cavities. Each cavity impedance was measured by a stretch wire method. The injection and extraction kickers, low field magnetic septa for FX and SX and resistive wall impedances are added to the RF impedance. The beam loading of the fundamental and second harmonic RF cavities

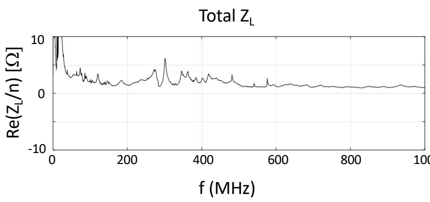


Figure 6: Real part of longitudinal coupling impedance.

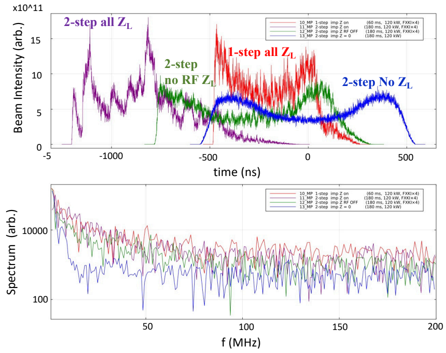

Figure 7: Simulated beam time structures and FFT spectra.

is compensated by a feedback system for the harmonic frequency within $h = 9 \pm 3$ and $h = 18 \pm 3$, respectively. The impedance in such a frequency range is set to zero. Figure 7 shows the debunched beam time structures and FFT spectra obtained by the simulations at 120 kW equivalent beam power. The initial beam at P3 is derived from an acceleration simulation without the impedance effect under Fig. 1 right condition. The red line is at 60 ms from P3, a critical timing for the 1-step debunch. The brown, green and blue lines are at 180 ms from P3, critical timing for 2-step debunch. The brown line includes all impedances, the green line excludes the RF part, and the blue line excludes all impedances. The microwave structure of several tens of MHz is seen for 1-step debunch (red). For 2-step debunch, the microwave structure is suppressed. A several MHz structure is observed in the brown line. This structure disappears without the RF impedances.

## EC WAKE AND TRANSVERSE BEAM SIMULATION

The interaction between the electron cloud and the beam can be represented as a wake function [8], which is convenient for simulating the transverse coherent oscillation. The beam has a fixed Gaussian distribution, and the initial electron cloud, represented by macro-electrons, is also Gaussian. The Gaussian space charge forces are obtained by the Bassetti-Erskine formula [9]. The first beam slice passing through the electron cloud location has a perturbed position shift (e.g. ~ 1mm) from the origin. The macro-electrons are moved by the space charge force of the beam and the electron cloud. The next beam slice receives force from the moved macro-electrons. The wake function can be obtained by repeating this process. Figure 8 shows the horizontal

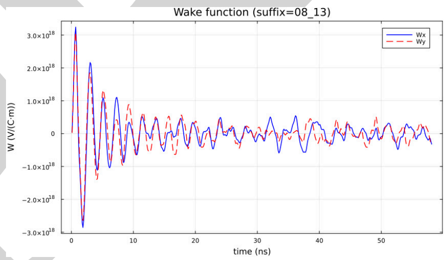

Figure 8: Wake function by EC-beam interaction.

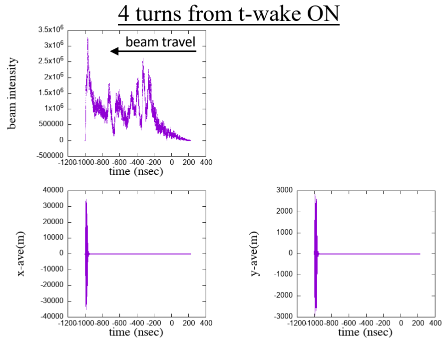

Figure 9: Transverse coherent oscillation by 6D tracking simulation.

(blue) and vertical (red) wake functions. The proton and electron line density are chosen to be $1.5{\times}10^{11}$ and $1.0{\times}10^{11}$ /m from Fig. 3. The horizontal and vertical rms beam emittances are $0.32\pi$ and $0.30\pi$ mm·mrad, respectively. The initial electron cloud beam size is chosen to be three times as large as the beam size.

Figure 9 shows the results simulated by the 6D tracking simulation code mentioned in the previous section. The initial beam at P3 timing was tracked longitudinally up to 34310 turns, and then the 6D tracking started. The ring lattice has a smooth approximation and electron cloud wake kicks are divided into 10 in the ring. The beam is rapidly blown up transversely and stopped after 4 turns (179.5 ms from P3). The size growth time is estimated to be 0.24 turn. The strong electron cloud wake is assumed to be distributed over the whole ring. This could lead to an overestimation for the coherent oscillation.

## CONCLUSIONS

The MR 30 GeV slow extraction has successfully achieved the beam power of 95 kW with a high extraction efficiency above 99.6% . However, a higher beam power for the slow extraction is limited by a transverse beam instability that occurs in the debunching process. The transverse beam instability associated with the electron cloud is estimated to be triggered by longitudinal microwave and peaky beam structures. An electron cloud simulation can roughly predict the electron cloud flux measured by an electron cloud monitor. A longitudinal beam simulation with longitudinal coupling impedances in the debunching predicts time structure modulations, which qualitatively explain the measured modulation. A preliminary 6D tracking simulation, in which the EC-beam interaction is modeled as a wake, predicts a strong coherent transverse oscillation with a growth time shorter than one turn. We will continue this comprehensive simulation work to understand the mechanism deeply and to suppress the beam instability at higher beam power.

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