E-cloud observations and simulation at J-PARC

K. Ohmi
T. Toyama, B. Yee-Rendon, M. Tomizawa and R. Muto

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Japan Proton Accelerator Research Complex

Kamioka
Tokai, Ibaraki

LINAC
45 mA (50 mA)
3 GeV RCS
500 kW (1MW)
← operation
←(goal)

30 GeV MR
FX mode 500 kW (750 W)

Hadron hall
SX mode 50kW (100kW)

ν detector
Two operation modes

Fast Extraction (FX)

Red line: DCCT
Blue line: Kinetic energy
Beam power: 490 kW
Machine cycle: 2.48 s
Top energy: 30 GeV

Slow Extraction (SX)

(1) Coasting beam slow extraction

Red line: DCCT
Blue line: Kinetic energy
Beam power: 51 kW
Machine cycle: 5.20 s
Top energy: 30 GeV

(2) Bunched beam slow extraction
Electron Cloud appears . . .

FX mode
- after large modification of vacuum components (usually long shutdown)
- accompanying vacuum pressure rise,
- scrubbing run of a few days is effective to reduce the pressure rise
- no issue during routine operations
- Beam intensity will increase from $2.5 \times 10^{14}$ ppp $\rightarrow$ $3.3 \times 10^{14}$ ppp in future
- e-cloud is not foreseen because of higher incident e$^-$ energy

SX mode
- at the debunching process at the flat-top
- accompanying vacuum pressure rise,
- connection to transverse instabilities is not clear (only one sample)
- very slow decrease of the electron signal $\sim$ a few % reduction / year
- still potential risk
- Beam intensity will increase from $5.5 \times 10^{13}$ ppp $\rightarrow$ $1.1 \times 10^{14}$ ppp in future
Electron cloud detectors (ECD)

Figure 1: The ECD installed at MR of J-PARC.

Figure 2: Schematic view of the ECD at J-PARC MR. Courtesy of R. J. Macek.
FX mode

ATAC/MR status Mar-1-2018

10

MR vacuum status

x10


Scrubbing

Beam power [kW]

Vacuum pressure [Pa]

Beam Power

Scrubbing

Beam Power(SX)

24 SSSs in Arc, Drift space in Ins(FW,Inj, Exciter, IPM, RF, etc), Collimator, Inj, FX, ESS1, ESS2, SMS1, SMS2, #085

Oct. 2017 - Feb. 2018
B. Yee-Rendon 410/24/17

**FCT signal**

- **Injection**
  - Voltage (V) vs. Time (ns)

**Electron cloud detector signal**

- **Injection**
  - Voltage (V) vs. Time (ns)
  - Interested region

- Input impedance = 1 MΩ
  - 10 mV → 10 µA

EC peaks at four injections

EC signal decreases after a few days
EC at the debunching process at the flat-top

Beam intensity ~ $4 \times 10^{13}$ protons

SX mode

No EC

With EC

Beam intensity ~ $4 \times 10^{13}$ protons

Longitudinal single bunch instability

Longitudinal couple bunch instability

One turn of the ring
Beam conditions where EC appears

EC presence depends on the RF phase at MR injection and the beam intensity / beam power

Larger RF phase results longer bunch length before debunching.
Electron cloud build up is triggered by longitudinal single bunch instability which is induced by longitudinal couple bunch instability.

Table 1: Relevant beam parameters during the SX operation of MR.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>m</td>
<td>1567.5</td>
</tr>
<tr>
<td>Energy</td>
<td>GeV</td>
<td>30</td>
</tr>
<tr>
<td>Power</td>
<td>kW</td>
<td>38.2</td>
</tr>
<tr>
<td>Bunch population</td>
<td>10^{13}</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Figure 4: The beam current signals for events with and without electron cloud in the time domain, top and bottom left, respectively. The corresponding Fourier transform plots are shown in right side in the same order.
Simulation for SX mode (debunching)

- PEI

Figure 1: The total SEY ($\delta_{\text{total}}$, green solid line) is the sum of the contribution for the elastic part ($\delta_{\text{elastic}}$, blue dot line) and the true secondaries ($\delta_{\text{true}}$, red dot line).

Figure 4: The comparison of the total electrons generated by the four intensities simulated at the two different times (5 ms and 75 ms after P3). The model used a $\delta = 1.6$ and $E_{\text{max}} = 200$ eV.
Simulation for SX mode (debunching)

Simulation with the sinusoidal beam density modulation

![Graph showing electrons produced in simulations vs. signal frequency](image)

**Figure 6:** Electrons produced in the simulations vs. the frequency of the sine signal at different intensities, using $\delta = 1.1$ and $E_{max} = 200$ eV.

Frequency spectrum of the beam measured by the Fast CT

**Graph showing frequency spectrum**

30 – 50 MHz → EC appears

“Multipactor condition” may be satisfied
Electron frequency and instability threshold

- Electron frequency bounded in proton beam potential

\[ \omega_{e,y}^2 = \frac{\lambda_p r_e c^2}{(\sigma_x + \sigma_y)\sigma_y} \]

- \( \omega_{e,x} = \omega_{e,y} = 32 \text{MHz} \ (2.8 \times 10^{13} \text{ ppp}),\ 40 \text{ MHz} \ (4.2 \times 10^{13} \text{ ppp}) \) for \( \sigma_{xy} = 7.5 \text{mm} \).

- \( \lambda_p = \text{averaged proton line density} = 1.8 \times 10^{10} - 2.7 \times 10^{10} \text{ m}^{-1} \).

- These frequencies are consistent with the electron amplification in the previous page.

- Threshold of the beam instability

\[ \lambda_{e,th} = \frac{2\gamma \omega_e |\eta_p|\sigma_p (\sigma_x + \sigma_y)\sigma_{x,y}}{\sqrt{3}cQr_p\beta_y} = 7.6 \times 10^7 \text{ m}^{-1} \]
Simulation for SX mode (debunching)

- **PyECLoud**

- Seed: Ionization Gas* (H was used as residual gas).
- Beam profile: FCT measurements at SX mode.
- SEY: $\delta = 1.7$, $E_{\text{max}} = 287$ eV, $R_0 = 0.8$.
- Tracking simulations: 15 turns.

**Figure 1:** The total SEY ($\delta_{\text{total}}$, green solid line) is the sum of the contribution for the elastic part ($\delta_{\text{elastic}}$, blue dot line) and the true secondaries ($\delta_{\text{true}}$, red dot line).
Figure 5: Left: the beam current; right: the comparison of the electron flux signals measured (green dot line) and the simulated (blue dot line). The values corresponded at 75 ms after the beginning of debunching.
**Time evolution of the EC**

- **Peak flux**
  - Measurements
  - Simulations

- **Total charge**
  - Measurements
  - Simulations

**Trend is reproduced.**

This suggests the longitudinal beam profile affects the EC growth.

The discrepancy may come from the estimation error of detector efficiency *etc.*
Simulation for FX mode

Parameters

\[ \delta = 1.7. \]

\[ E_{\text{max}} = 300 \text{ eV}. \]

\[ R_0 = 1. \]

Proton per bunch \( \sim 4.2 \times 10^{13} \). (Bunch length \( \sim 54 \text{ ns} \))

Measured longitudinal profile by Fast CT Tracking turns = 6.
Proton density vs Electron density

Electron cloud density is very small comparing to the proton density.
Electron energy distribution

Electron energies are in higher energies at which SEY is less than 1
Summary

- Measurements

✓ SX mode: EC appears during debunching process. EC and vacuum pressure rise in the whole ring. Larger initial RF phase offset suppresses the EC growth. possible scenario:
  - suppresses longitudinal coupled-bunch oscillation
  - smoother debunching
  - no EC

✓ FX mode: EC only appears after vacuum component modification. EC & vacuum pressure rise decrease after a few days.
• Simulation

✓ SX mode: EC growth is reproduced with spiky beam profiles. Details of the spiky beam profiles affects the EC growth. Beam profile structure around 40 MHz seems to satisfy multipactor condition at the beam intensity ~ $4 \times 10^{13}$ protons.

✓ FX mode: EC estimated to be negligibly small with the beam profile at $4.2 \times 10^{13}$ p/bunch, 8 bunches.
References

B. Yee-Rendon et al., “ELECTRON CLOUD STUDIES AT J-PARC MAIN RING”,
    presented in ICFA mini-WORKSHOP ON IMPEDANCES AND BEAM INSTABILITIES IN PARTICLE ACCELERATORS,
B. Yee-Rendon et al., “PyECLOUD SIMULATIONS OF THE ELECTRON CLOUD FOR THE J-PARC MR”,
B. Yee-Rendon et al., “ELECTRON CLOUD STUDY AT SX OPERATION MODE AT J-PARC MR”,
    Proceedings of 13th Particle Accelerator Society of Japan, Chiba, Japan, August 8 - 10, 2016, p.149.
B. Yee-Rendon et al., “ELECTRON CLOUD MEASUREMENTS AT J-PARC MAIN RING”,

and references therein.
APPENDIX
Model for low electron energy
PyECL OUD


Spectrum energy secondary electrons


Observation of the instability

One event during SX mode
Transverse instability triggered the e-cloud or vice versa → not clear

Beam intensity = $5.5 \times 10^{13}$ protons (51 kW)

Electron cloud signals larger than normal shots

Beam loss MPS stops the operation

Pressure rise larger than normal shots

Vertical oscillation observed
Next shot (to check if the machine comes back to the normal condition)

Run 78  Shot 130618  at 18/02/03 01:04:10
Run 78  Shot 38220  at 18/01/25 14:51:20
All relevant signals are lined up in the same time scale
EC signal and $\Delta x$, $\Delta y$ signals

Hor. / Ver. oscillation → frequency analysis

Oscilloscope: LeCroy HDO6034
500 MS/s, LPF=200MHz

Shot 130617 at 18/02/03 00:58:35
50.69 kW 18/02/03 01:02:47