Electron cloud instability in J-PARC simulations

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J-PARC/KEK
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J-PARC/JAEA
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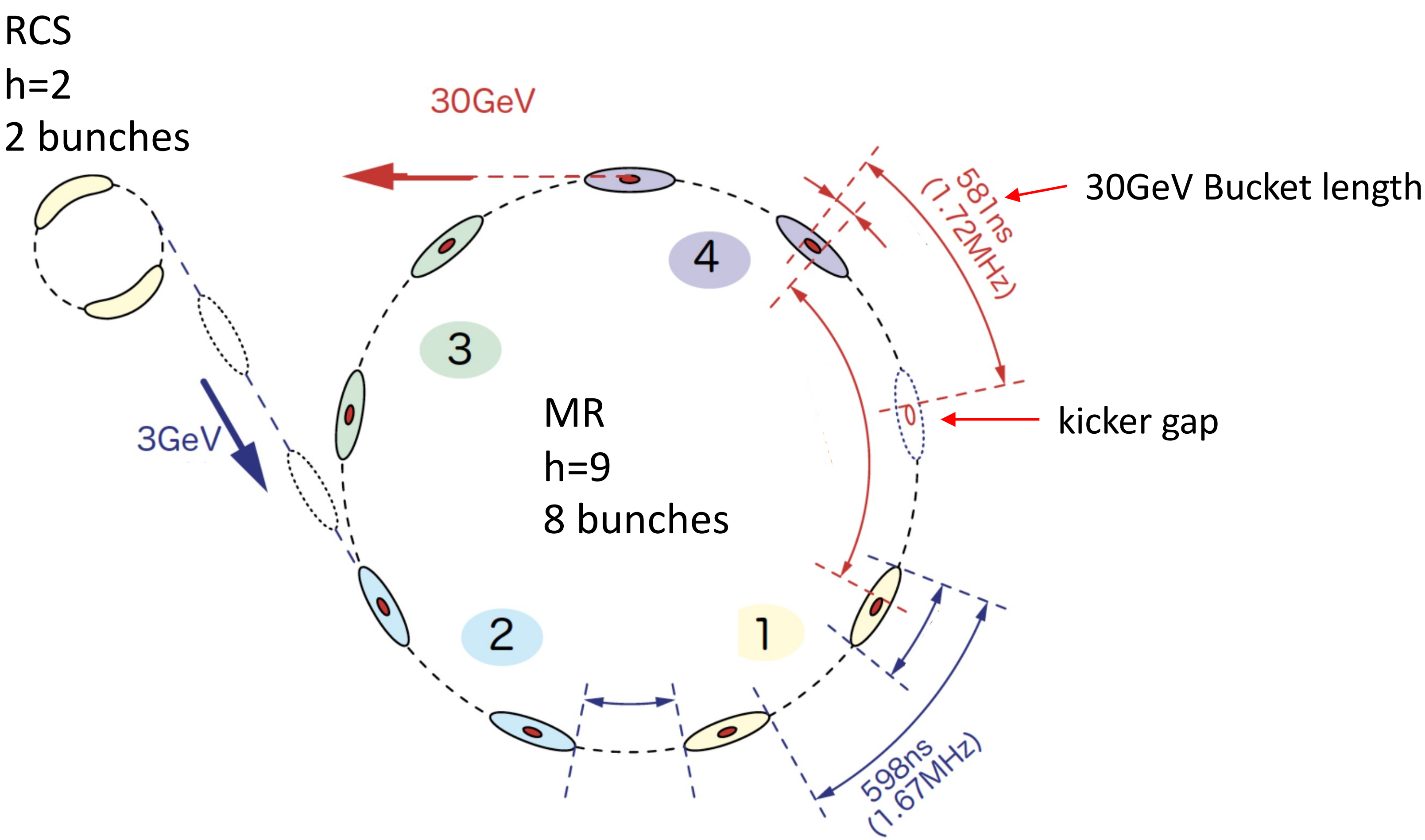
1. Instability observed in slow extraction operation
2. Longitudinal beam simulation in beam debunching
3. Electron cloud generation simulation (preliminary)
4. Summary and future plan

J-PARC Main Ring (MR)
proton beam

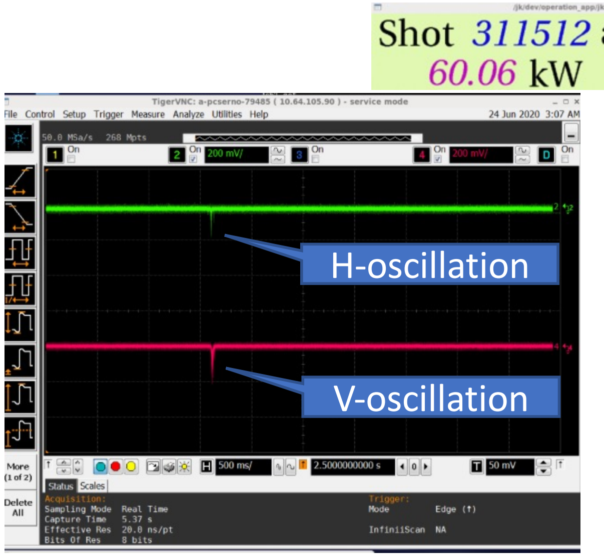


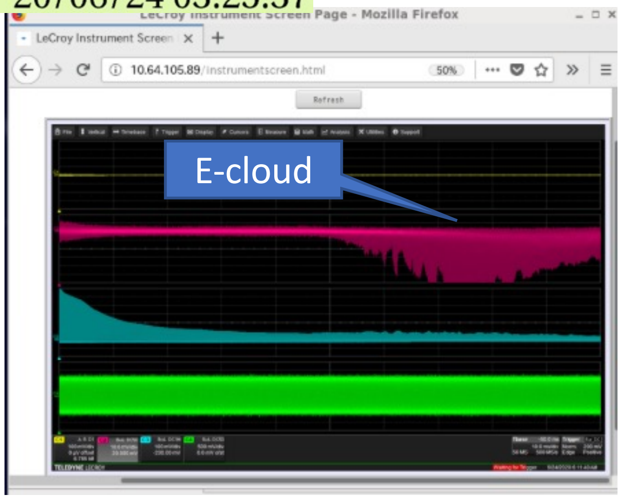
RF is turned off for debunching before slow extraction at 30GeV

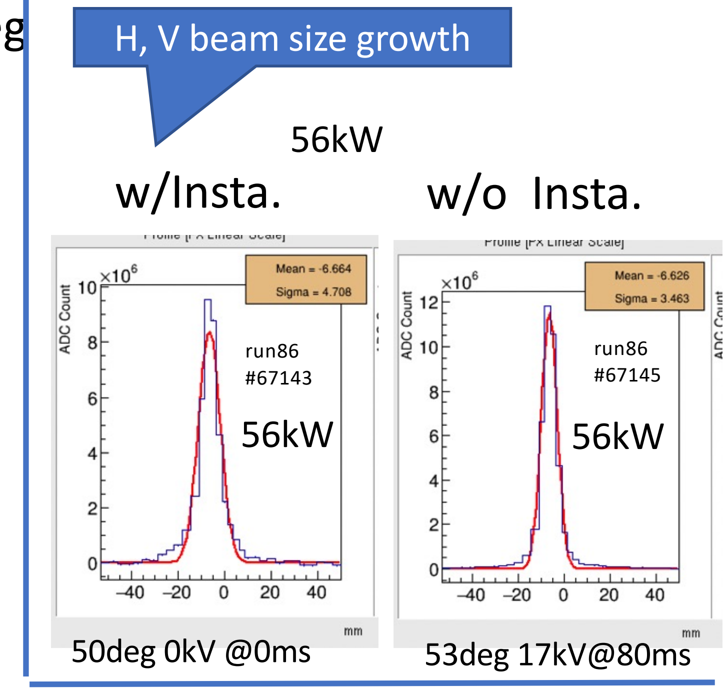
Beam Instability at debunch timing

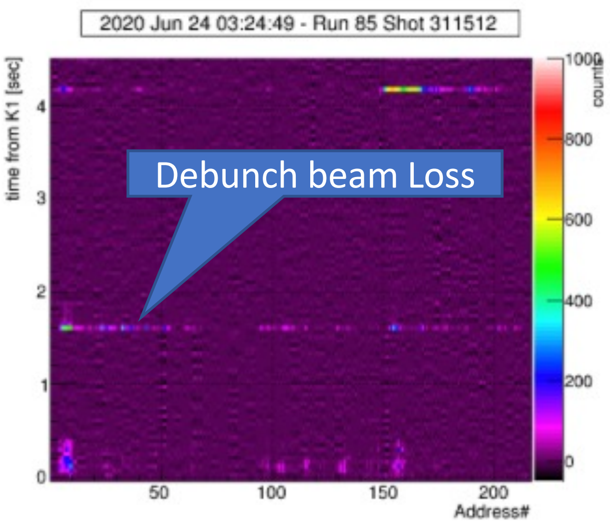
Currently Limiting SX beam intensity (large beam loss for SX)

Abort destination, 60kW debunch , RF phase offset 65deg

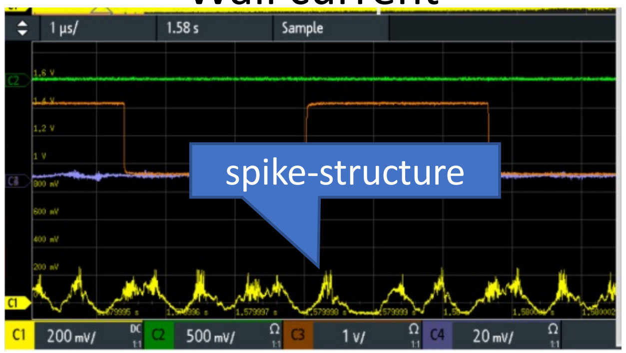




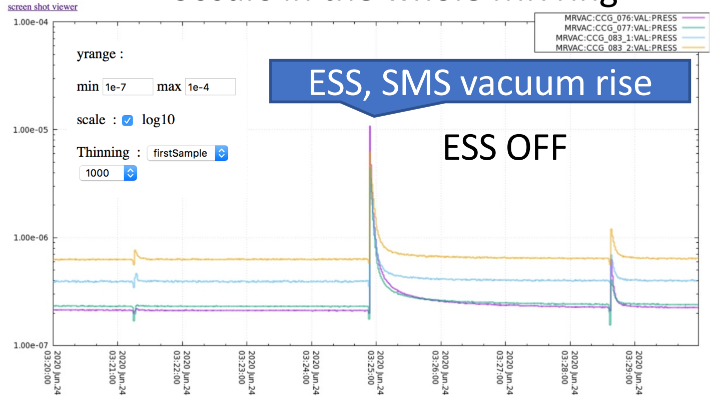




Wall current



occurs in the whole MR ring



The timing the instability seen is ～60ms from the debunch start (P3) corresponding to time adjacent beams overlap

Our current strategy to mitigate the instability with e-cloud is to improve the longitudinal beam structure

Microwave instability Longitudinal Keil-Schnell (K-S) criterion

$$\left|\frac{Z_L(n\omega_0)}{n}\right| \leq F \cdot \frac{|\eta|\beta^2 E_0/e}{I_p}\left(\frac{\Delta p}{p}\right)^2_{FWHM},$$

Increase longitudinal emittance

Phase offset injection
2 step debunch

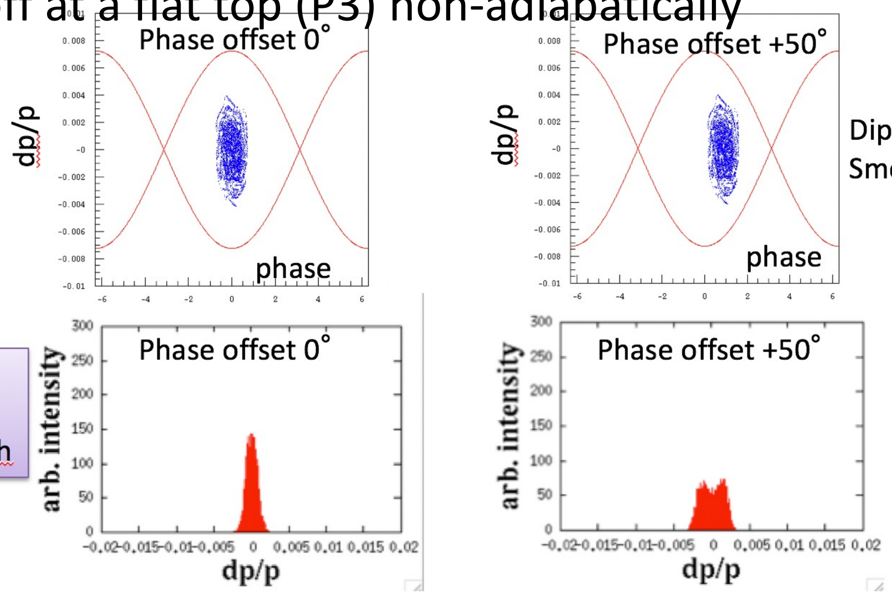
To reduce ZLs are also important if possible

Current Mitigations of Beam Instability

- Beam injected to MR RF buckets with a phase offset (effective up to 50 kW from 30kW)
  256kV RF turned off at a flat top (P3) non-adiabatically

160kV
Injection

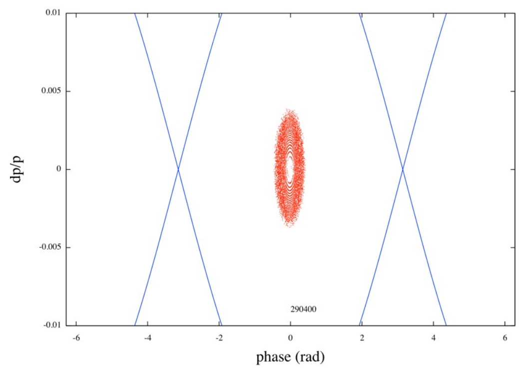
256kV
Flat top
Before debunch



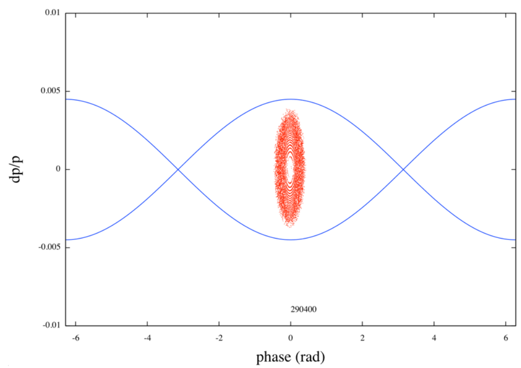
Dipole oscillation
Smear

- 2-step (voltage) debunch in combination with the phase offset injection
  Newly introduced from Dec., 2020
  ramped up the beam power for the user run from 50kW to 64.6 kW.

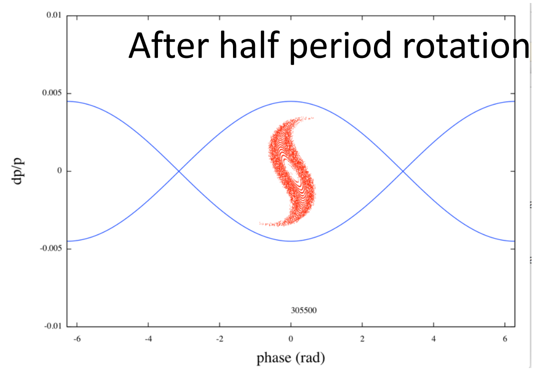
P3 256kV



P3 17kV (non-adiabatically)

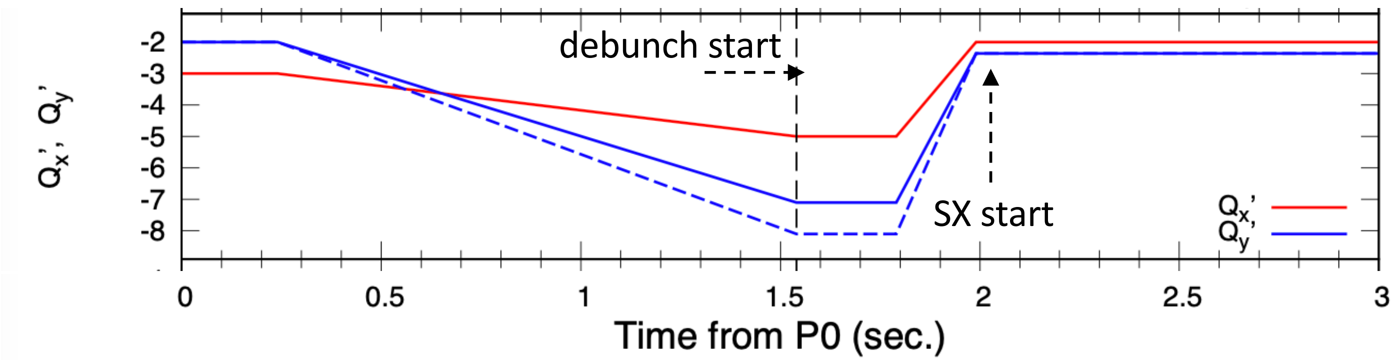


P3+80ms 17 -> 0 kV



Other Mitigations

・ weaken H,V chromaticity correction (negative value) during debunching
(direct transverse instability mitigation)
J-PARC slow extraction needs a small Qx’ for high slow extraction efficiency
This manipulation to move Q’ quickly is limited by Q’ correction PSs
-> partially works to suppress the instability, but not enough



・ RF Phase jump before debunching (increase momentum spread)
could not improved in a preliminary test

Plans
・ to introduce slippage change lattice during debunch to suppress L-instability
・ to introduce VHF cavity to increase L-emittance (large cost ～2M$)

Longitudinal coupling impedance

MR longitudinal impedances have been derived by

- stretched wire method measurements
  RF cavities (new)
  Gap-shorted RF cavities (new)
  FX kickers (> 1GHz) (new)
  Injection kickers (as before)
  correction kickers (as before)
  SX septa (as before)

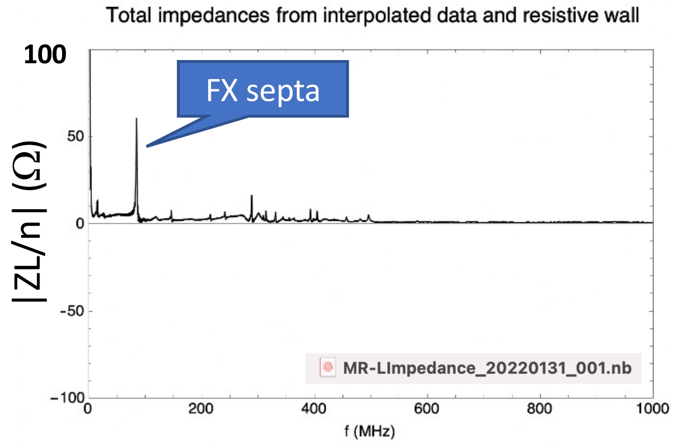
- CST (CST Studio Suite) simulations
  FX thin magnetic septa (till 2021) (new)
  FX eddy current septa (from 2022) (new)

(by T. Toyama, A. Kobayashi, M. Yoshii, et al.)

Total MR L-impedances (RF, FX-MS, SX-MS, FX-KI, INJ-KI,COR-KI, Resistive Wall)

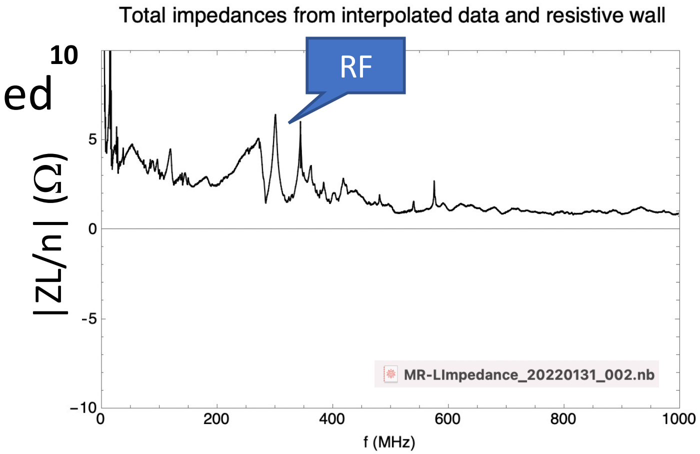
- case-1: 5.2s cycle, 2021 operation

5 RF cavities ON,   6 cavities shorted
old FXMS



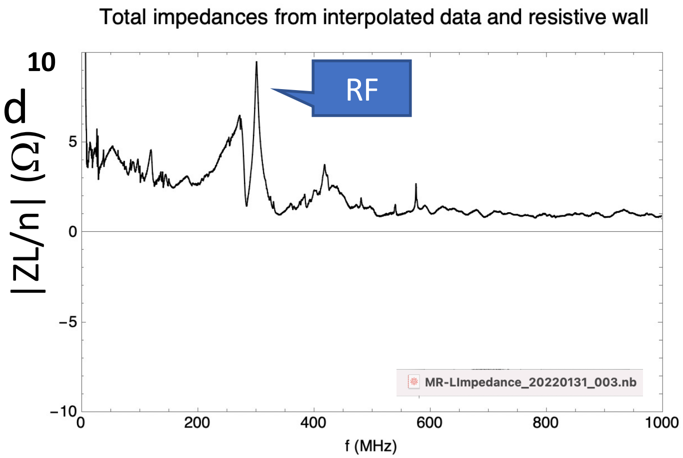
- case-2: 5.2s cycle, JFY 2022 operation planned

5 RF cavities ON,   6 cavities shorted
new FXMS



- case-3: 4.2s cycle, JFY 2022 operation planned

8 RF cavities ON,   3 cavities shorted
new FXMS

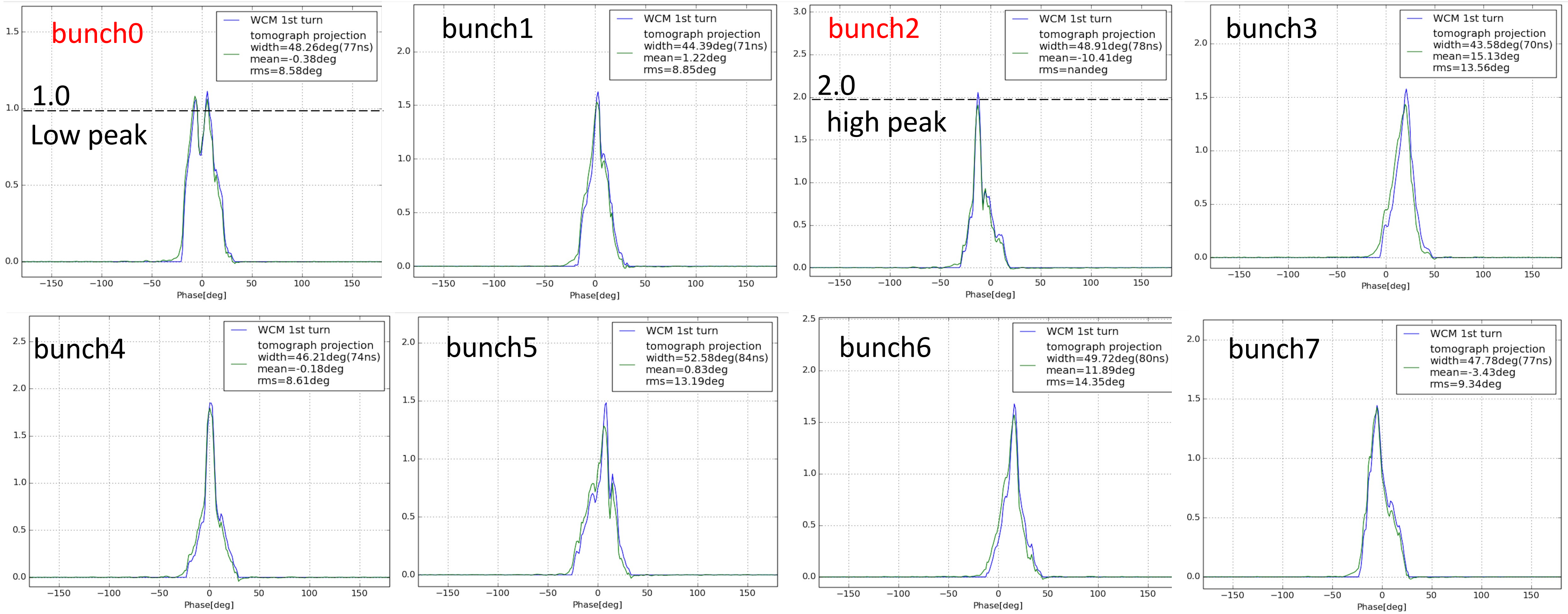


MR impedance models have been established

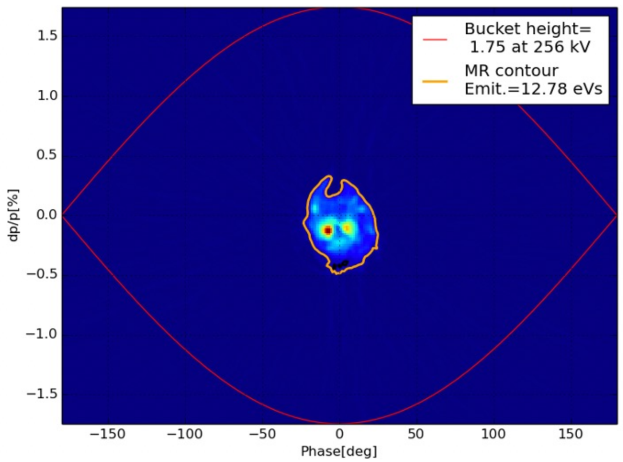
Initial proton beam distribution before debunching

Tomography projection (60kW)

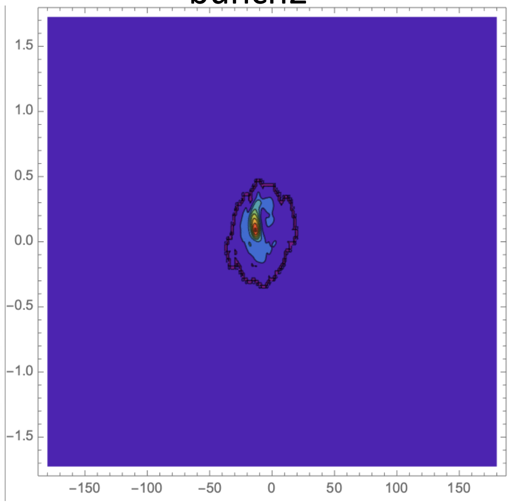
2021/05/13 Shot#16260 bunch0-7 (P3 timing)



bunch0



bunch2



- time-energy 2D distribution from tomography data used for longitudinal simulation w/ ZL
- The beam distribution Is rather different for each bunch
- Longitudinal bunch oscillation is expected to be improved by RF beam loading compensation from FF (9) and FB(8,10) to FB(8,9,10) only

Longitudinal tracking Simulation in Longitudinal impedance (ZL)

- Time domain
- ZL: total ring longitudinal impedances
- Wake function

$$W'(z<0) = \frac{2}{\pi}\int_0^{\infty} \mathrm{Re}Z_L(\omega)\cos(\omega z/c)\,d\omega$$

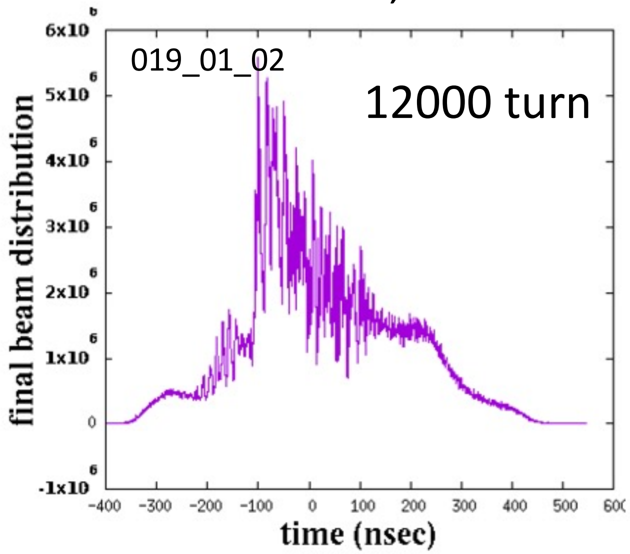
CHAO text:

- Beam loading voltage is derived from W’ and beam distribution
- Longitudinal kick at one point by the beam loading voltage
- Proton space charge force can be implemented directly as beam loading voltage

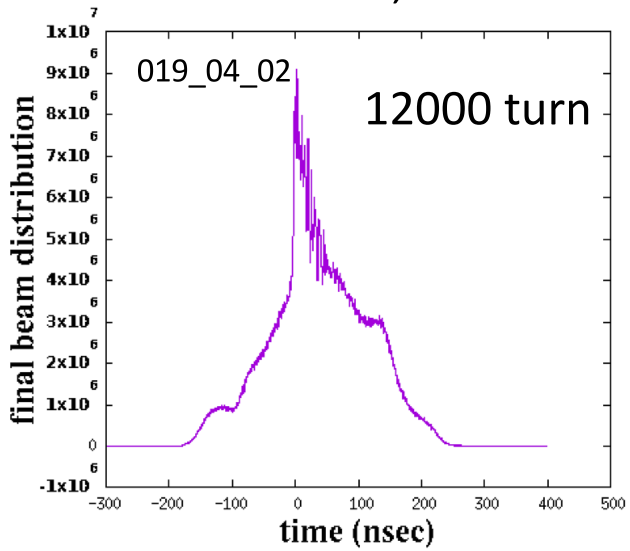
w/o 2step debunch simulation
(60kW beam,6.5x10^13ppp)

The spike structure appears as measured

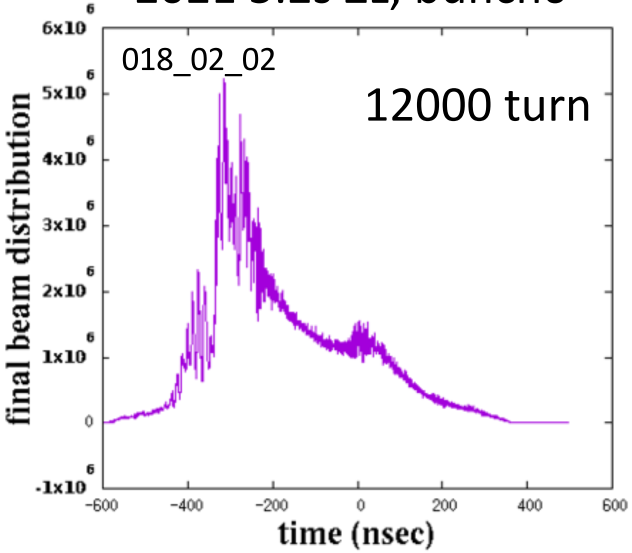
2021 5.2s ZL, bunch2



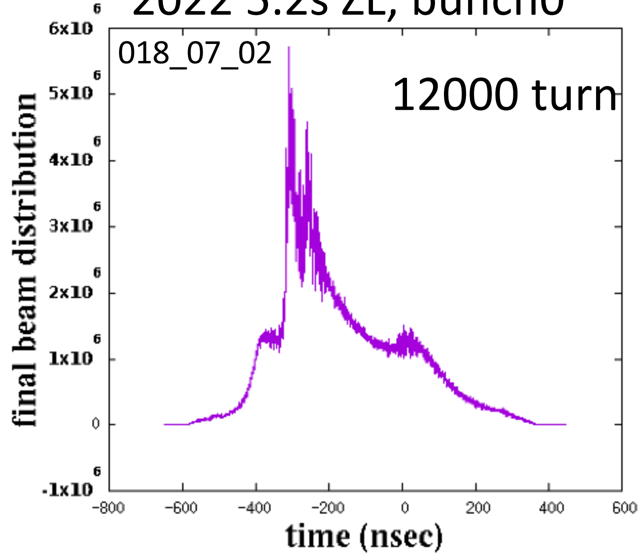
2022 5.2s ZL, bunch2



2021 5.2s ZL, bunch0



2022 5.2s ZL, bunch0

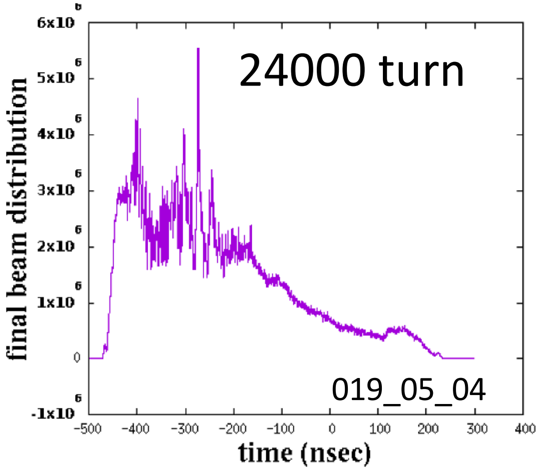


The spike structure is improved for 2022 ZL

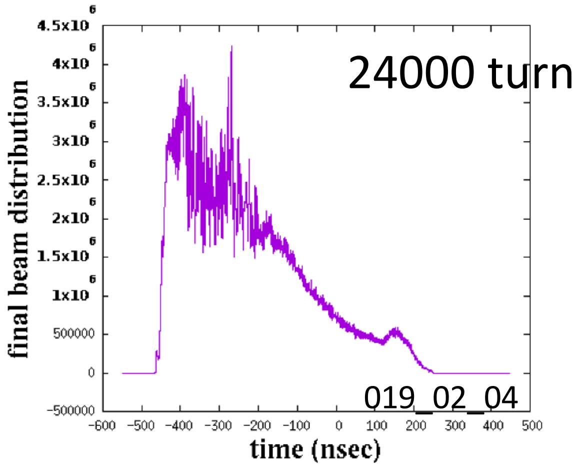
w/ 2step debunch simulation
(60kW beam,6.5x10^13ppp)

The spike structure is improved for 2step debunch for 2021 ZL

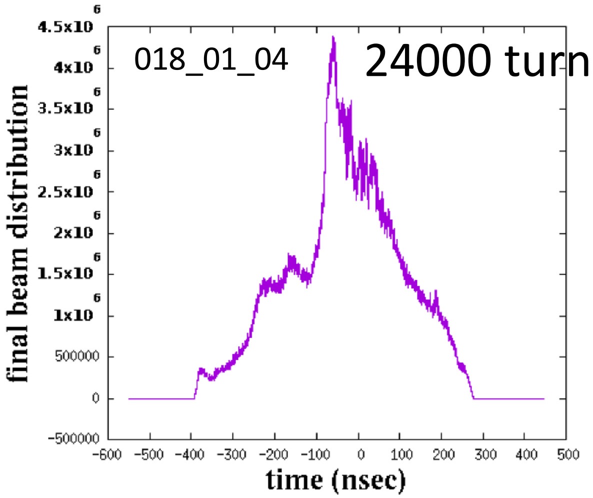
2021 5.2s ZL, bunch2



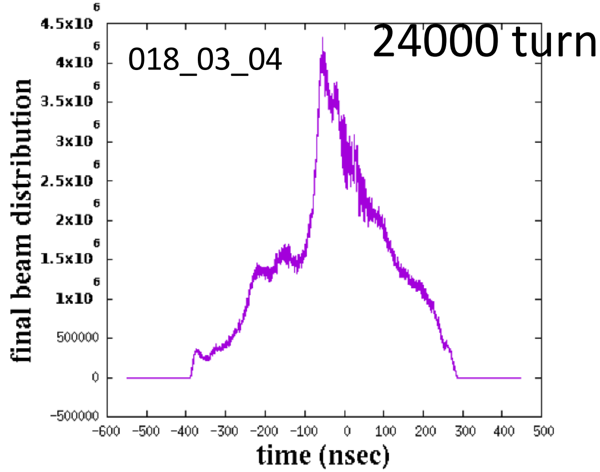
2022 5.2s ZL, bunch2



2021 ZL , bunch0



2022 5.2s ZL , bunch0



Electron Cloud Generation Simulation

Previous work

K. Ohmi

Bruce Yee-Rendon

- IOP Conf. Series: Journal of Physics Conf. Series 874(2017)012065 (by his code)
- Proc. of PASJ 2017, p.197 (by pyECLOUD)

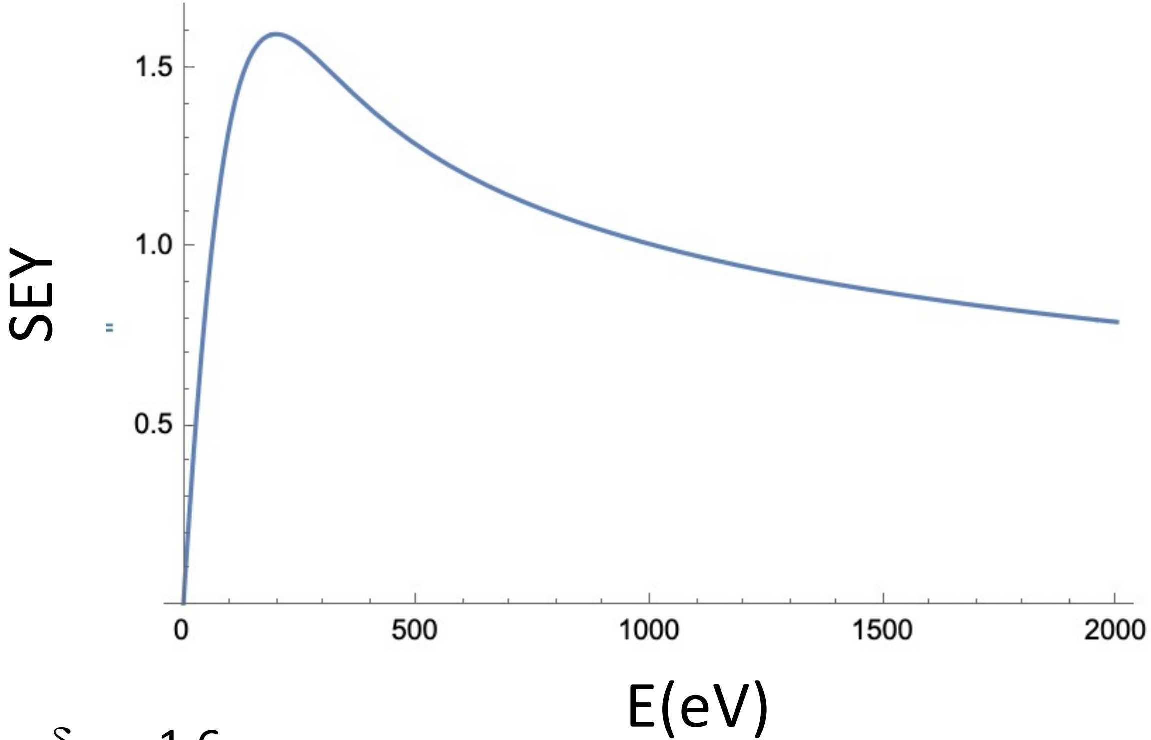
Current work

Independent simple code

- Axial symmetry of proton, electron beam distribution in a cylindrical beam duct
- Transverse proton beam distribution is Gaussian and no effect from electron cloud
- Longitudinal proton beam distribution can be flexible but frozen in the simulation (no synchrotron oscillation)
- Electron is initially generated by a residual gas ionization from proton collision
- Secondary electron has zero energy initially (approximately)
- No external field
- Space charge effect by electron cloud has been implemented but currently not completed

current simulation parameters:

- Ionization cross-section: 2Mb, vacuum pressure: 1x10^-6Pa, temperature: 300K
- Proton beam beam size: $\sigma_{\mathbf{rms}}$ =1.79 mm, r_{max}=5* $\sigma_{\mathbf{rms}}$
- beam duct r=70mm
- radial mesh 200
- longitudinal resolution 1ns

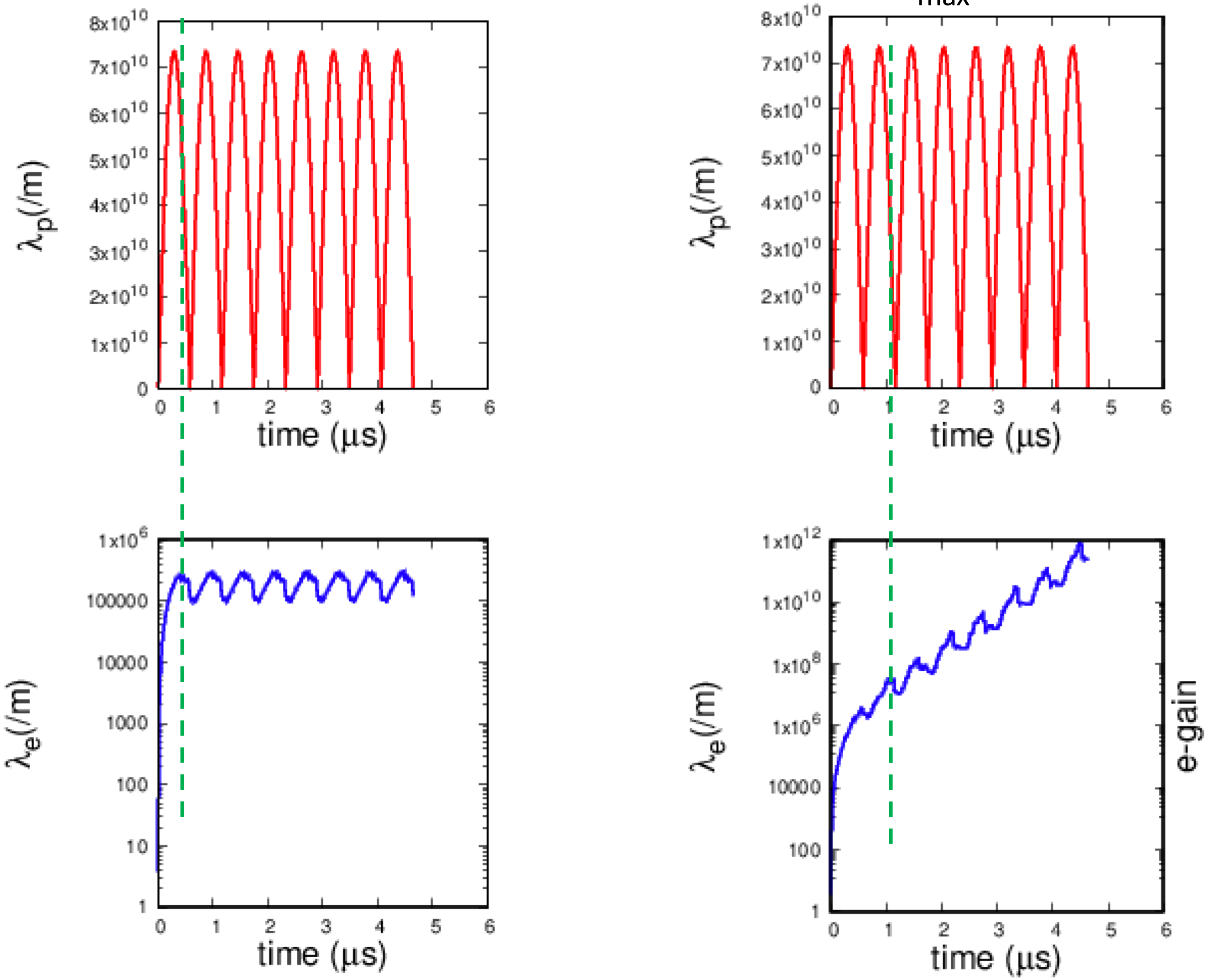


δ_{max}=1.6
$E_{max=}$ 200eV

SEY[E]= δ_{max} *1.11*(E/E_{max})^-0.35*(1 - Exp[-2.3*(E/E_{max})^1.35]) Ng, Textbook

1.721MHz (f_{rv}*h) Proton beam half-sine chain, 6x10^13 ppp

δ_{max}=1.1 0015_04 δ_{max}=1.6

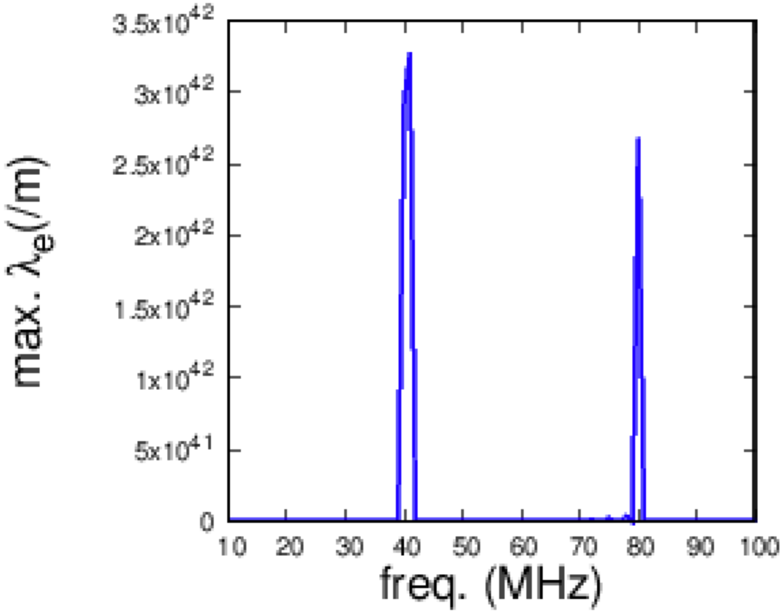


Electron generation peak is delayed from proton peak (trailing edge multipactering)

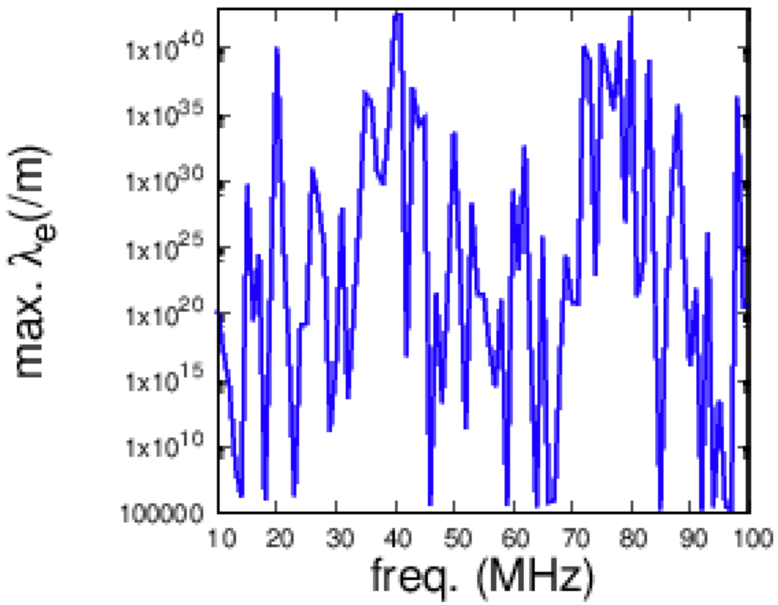
Proton beam half-sine chain, 6x10^13 ppp
10MHz to 100MHz every 1MHz
Maximum electron line density in 8/9 turn

0015_01

Linear scale

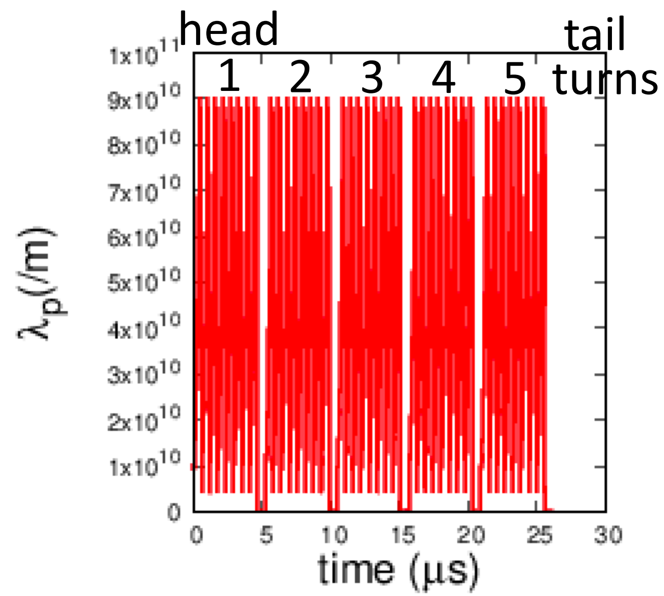


Log scale

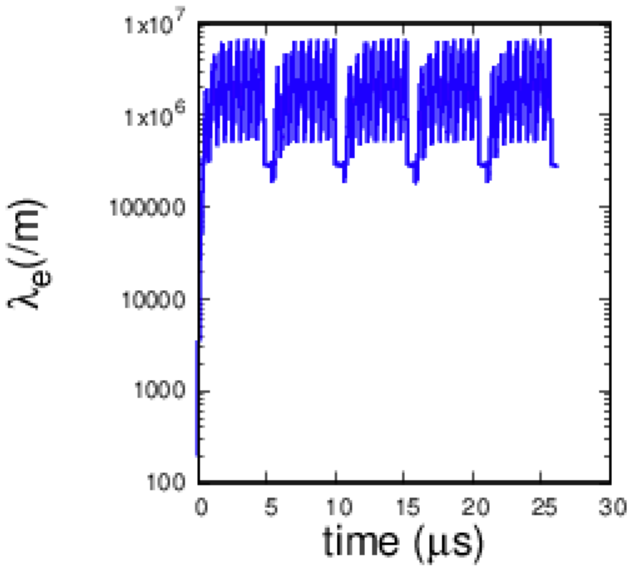


E-cloud is enhanced at 40MHz and its harmonics

E-cloud simulated in 5 turns (6x10^13ppp)

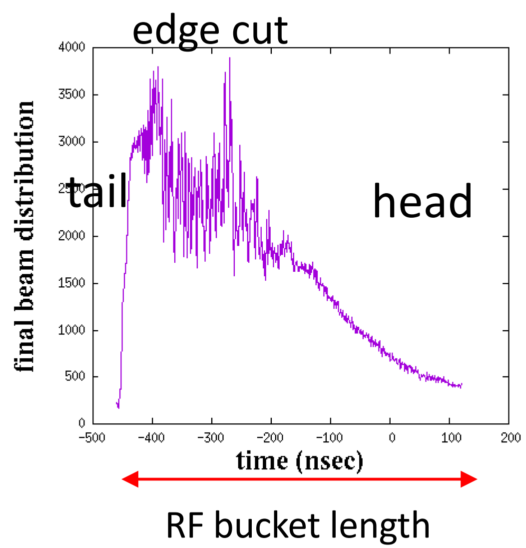


0013_08



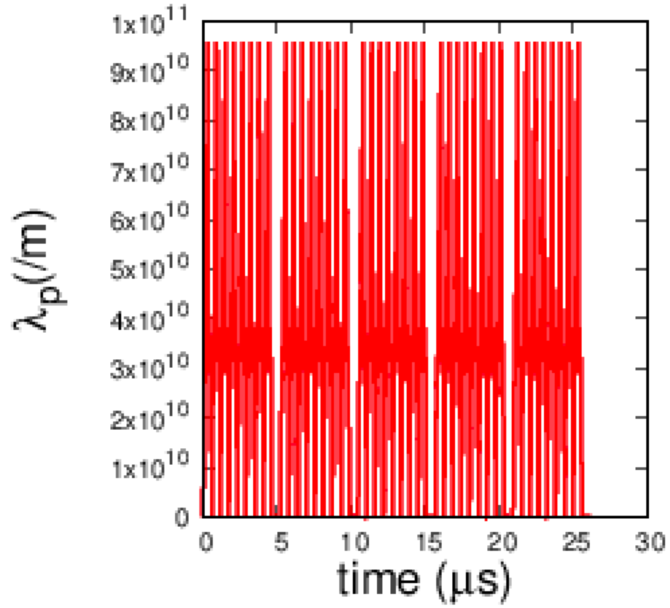
Proton distribution
L-simulation
w/ ZL: 2022,5.2s cycle
2 step debunch
Initial beam bunch2
24000 turn from FT start

This distribution is used for all bunches



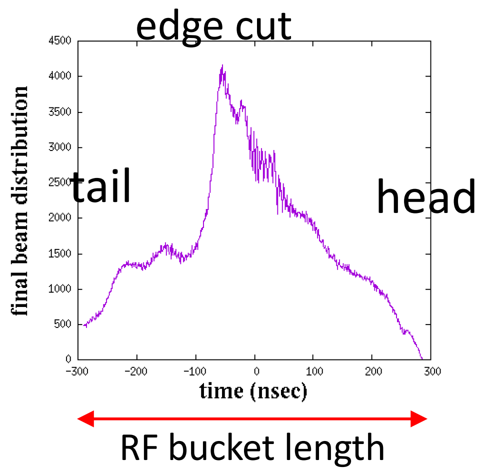
The e-cloud build-up in one turn is moderate.
E-cloud enhancement by
the micro-structure is not clear
The kicker gap rather resets the e-cloud

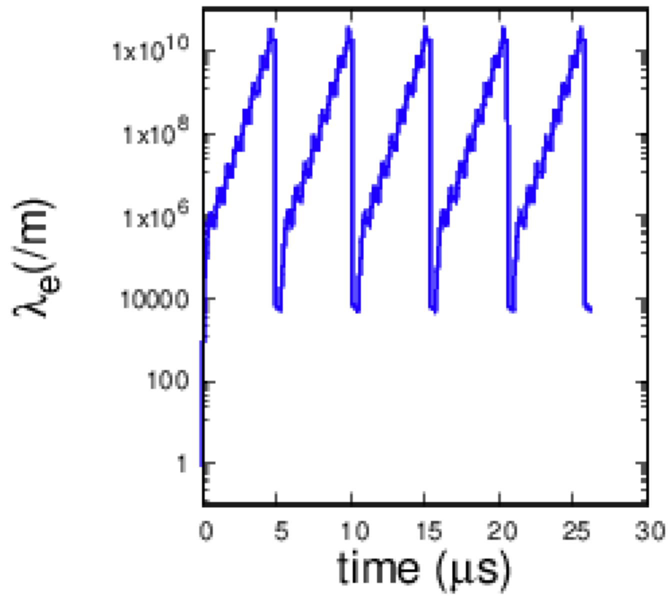
E-cloud simulated in 5 turns (6x10^13ppp)



Proton distribution
L-simulation
w/ ZL: 2022,5.2s cycle
2 step debunch
Initial beam bunch0
24000 turn from FT start

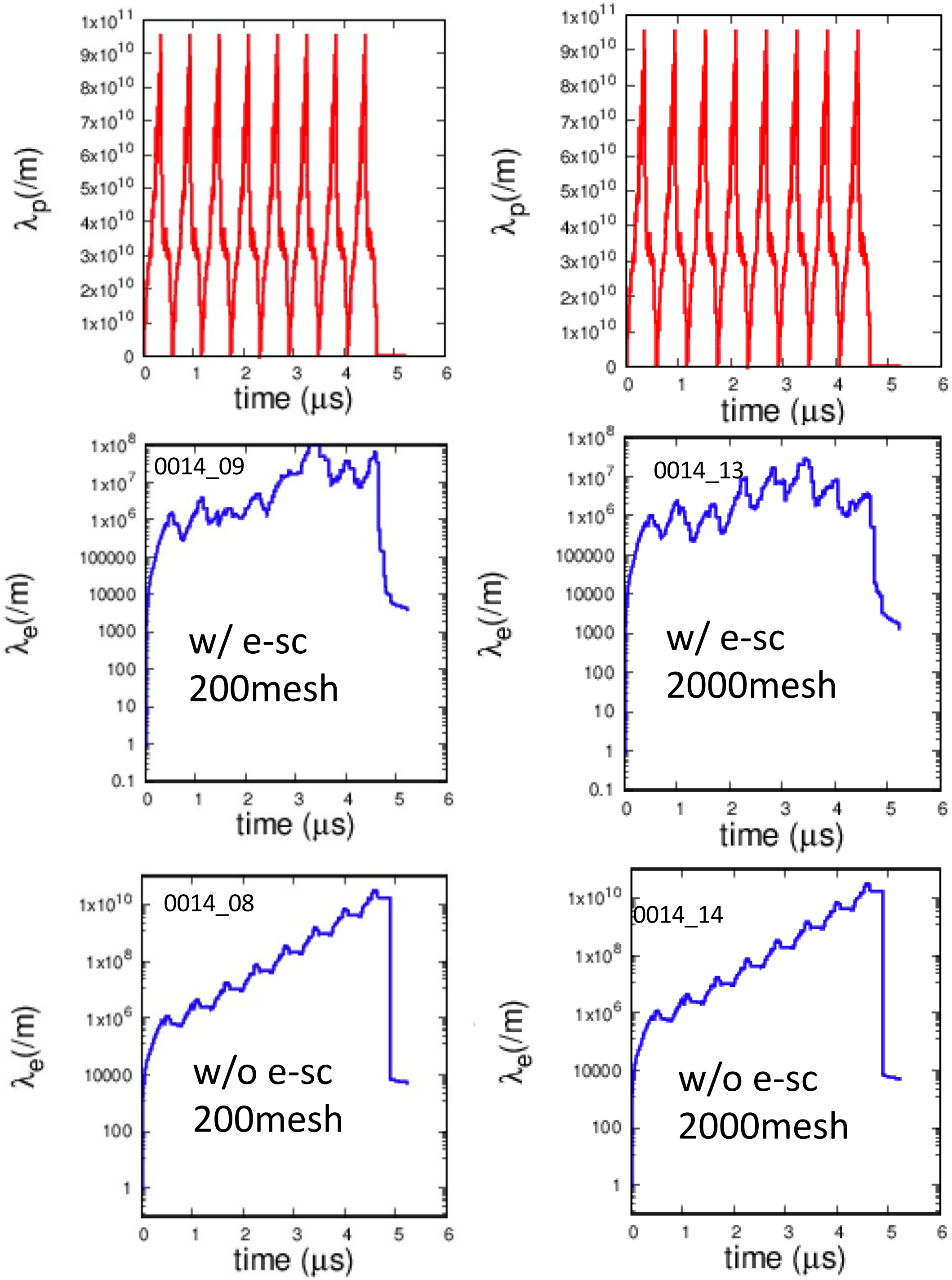
This distribution is used for all bunches





The e-cloud build-up in one turn is large!
The kicker gap rather resets the e-cloud

Electron space charge of e-cloud generation (very preliminary)



w/ electron space charge
depending on mesh size
The simulation accuracy should be improved!

w/o electron space charge
not depending on mesh size

Summaries and plans

What enhances e-cloud in debunching process for J-PARC SX ?

- Electron cloud simulation assuming axial symmetry has been conducted
  to know a rough e-cloud behavior
- E-cloud is strongly enhanced at 40MHz and its harmonics for half-sine chain distribution
- According to the current e-cloud simulation using proton distributions
  obtained by longitudinal beam simulation with MR ZL,
  e-cloud seems to be enhanced not by the micro-structure,
  by a macro-structure of proton beam, though further check and study is necessary.

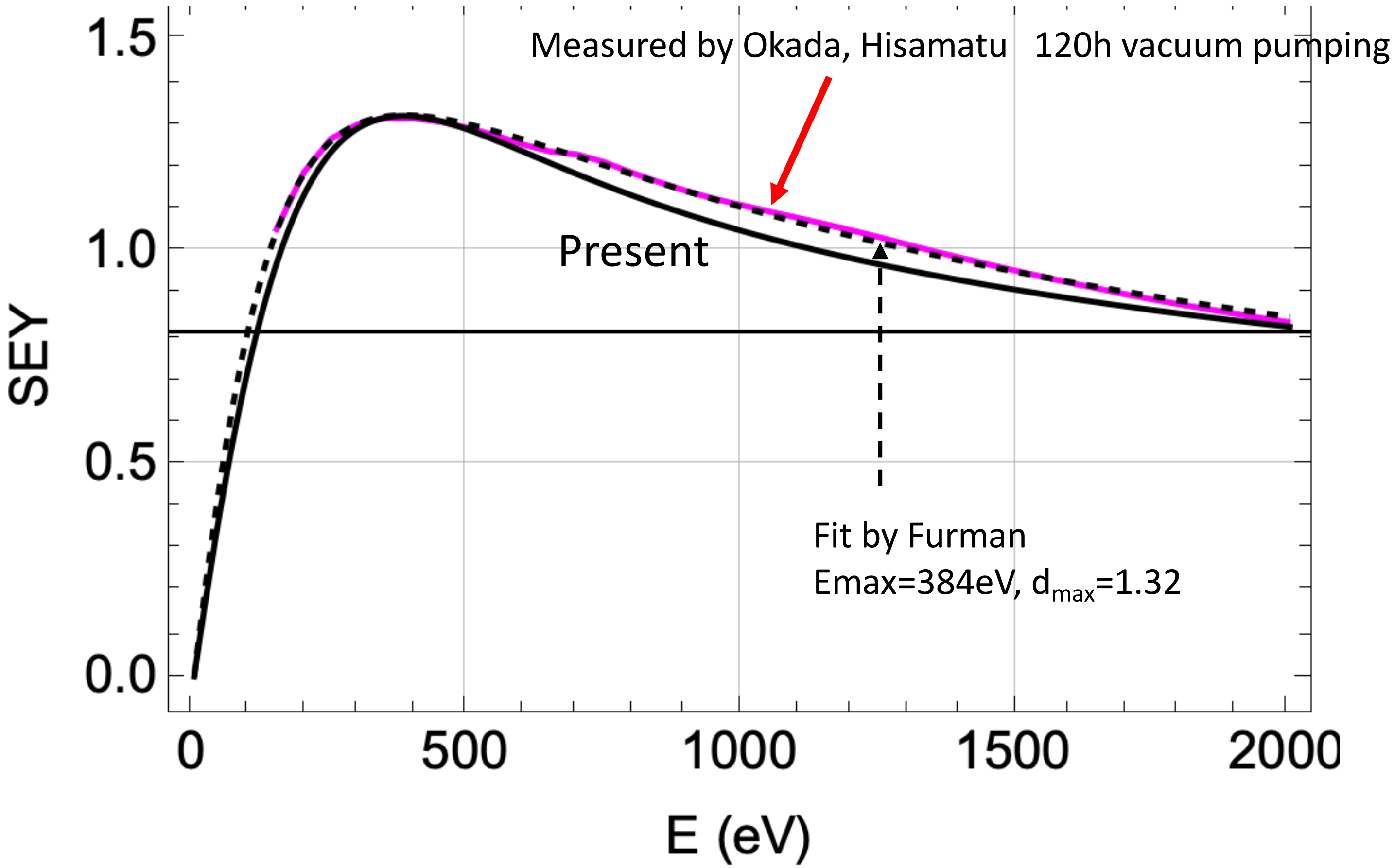
- use realistic SEY and SE-electron energy spectra
- Measured wall current data of proton beam will be used for the e-cloud simulation.
- Relation of beam overlap degree in adjacent beams and e-cloud will be examined.
- Electron space charge may play a important role for a high electron line density
- More accurate algorithm will be expected to be implemented.

More realistic/reliable simulation could be done
using existing codes (like PyECLOUD) developed by e-cloud experts

Any comments or suggestions from e-cloud experts are welcome!
masahito.tomizawa@kek.jp

SEY

by Toyama



SEY

by Toyama