J-PARC MR power upgrade toward the higher neutrino beam
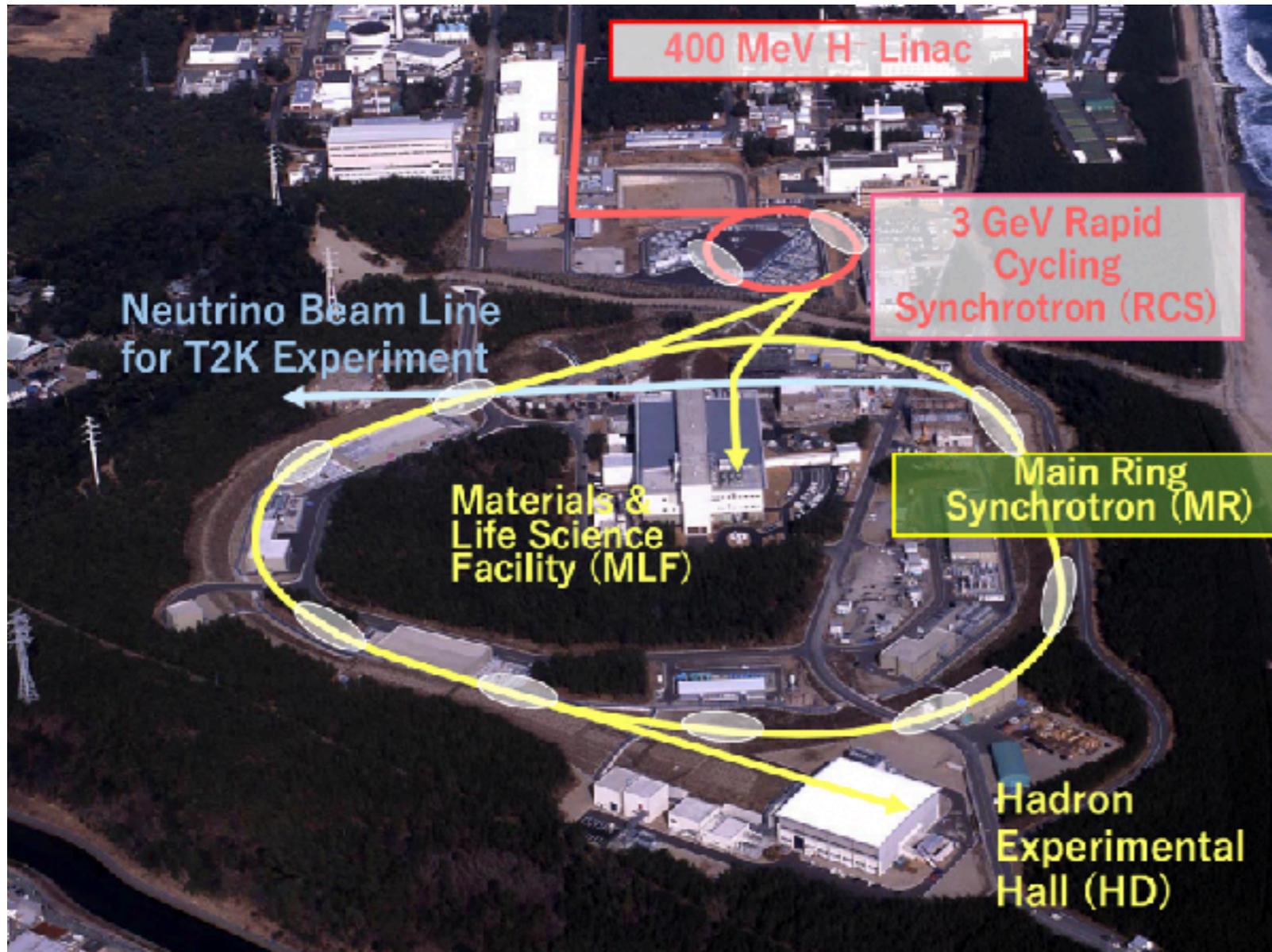
Aine Kobayashi

KEK/J-PARC

13 June 2019
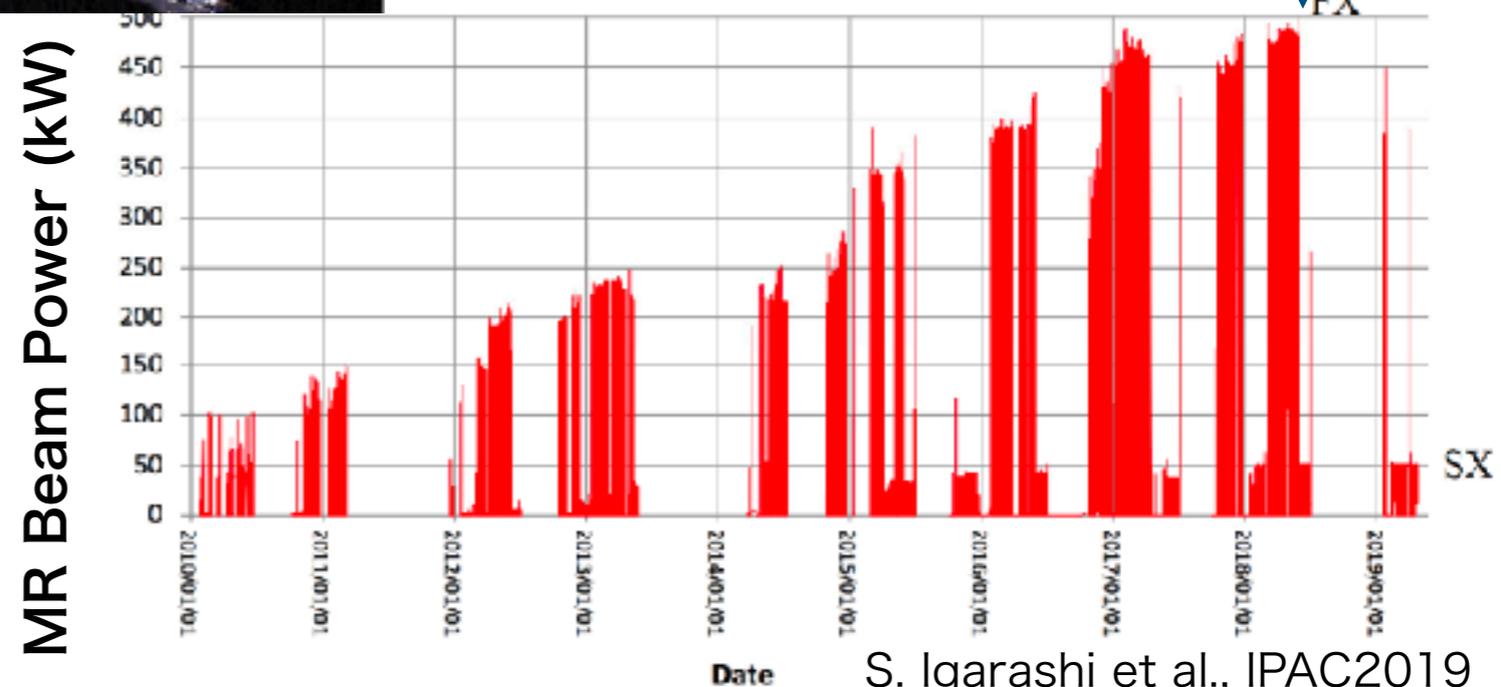
A02

Exploration of Particle Physics and Cosmology with Neutrinos Workshop 2019

400 MeV H⁻ Linac

3 GeV Rapid
Cycling
Synchrotron (RCS)

Neutrino Beam Line
for T2K Experiment

Materials &
Life Science
Facility (MLF)

Main Ring
Synchrotron (MR)

Hadron
Experimental
Hall (HD)

Slides from Y. Sato

500 kW

with beam power loss 700 W

FX

MR Beam Power (kW)

SX

Date

S. Igarashi et al., IPAC2019

Main upgrade programs

Faster cycling ：2.48 s →1.32 s for 750 kW→ 1.16 s for 1.3 MW

More accelerated protons： 2.6×10^{14} ppp → 3.3×10^{14} ppp

JFY	2017	2018	2019	2020	2021	2022	2023	2024
Event	New buildings →			HD target	Long shutdown			
FX power [kW]	475	500	500	500		>700	800	900
SX power [kW]	50	50	50	70		> 80	> 80	> 80
Cycle time of main magnet PS	2.48 s	2.48 s	2.48s	2.48s		1.32 s	<1.32s	<1.32s
New magnet PS	Mass production/installation/test →							
High gradient rf system								
2nd harmonic rf system	Manufacture, installation/test →							
Ring collimators	Capacity 2 kW				Capacity 3.5kW			
Injection system	Kicker PS improvement, Septa manufacture /test →							
FX system	Kicker PS improvement, FX septa manufacture /test →							
SX collimator / Local shields						Local shields →		
Ti ducts and SX devices with Ti chamber	Ti-ESS-1							
New BPM system			→					

Modified slides from S. Igarash et al., IPAC2019

2.48 s Cycle
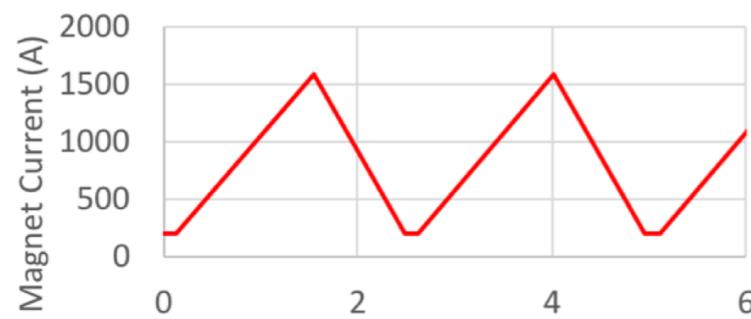
1.16 s Cycle
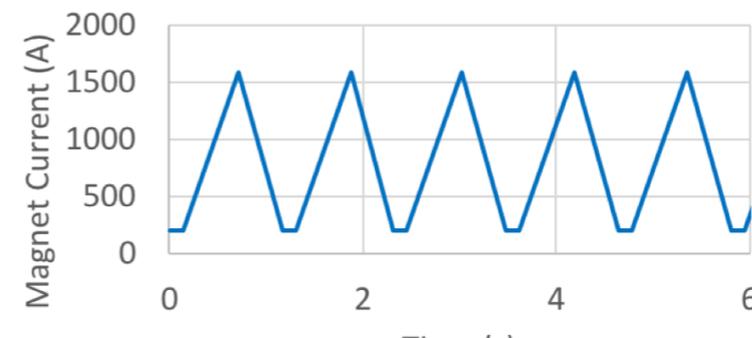
# Challenges from beam dynamics side

**beam power loss limits
the maximum output beam power!**

- betatron tune shift due to space charge or magnet power supply ripples

- non-linear resonances

- impedances seen by the circulating beam

- collective motion of the beam

Beam impedance

Circulating beam sees impedances
when passing through various beam
pipes and devices in the ring
  → beam becomes unstable
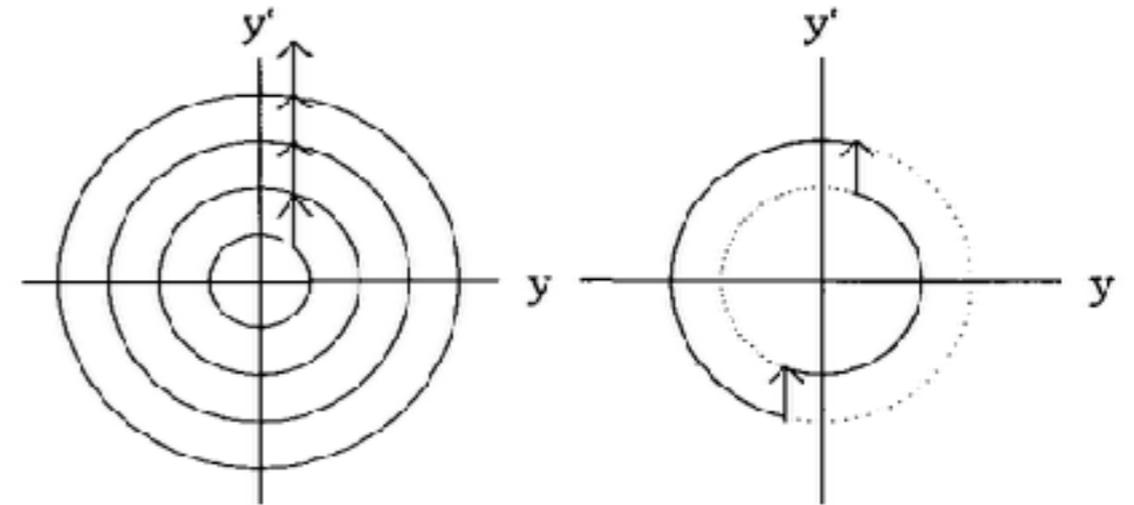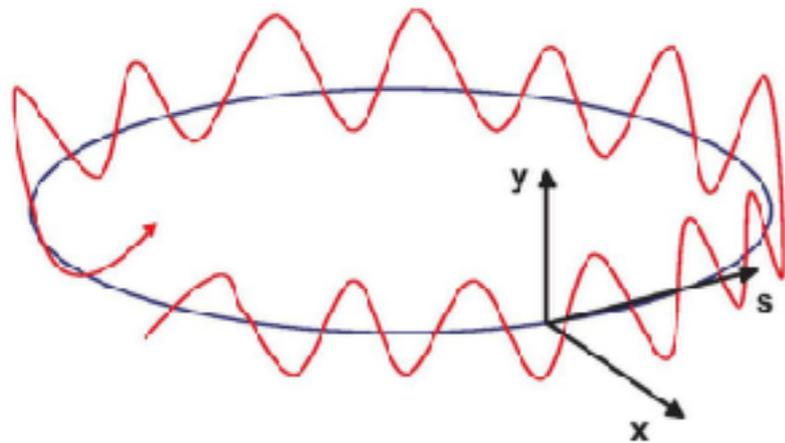 (= instability)
  → beam loss
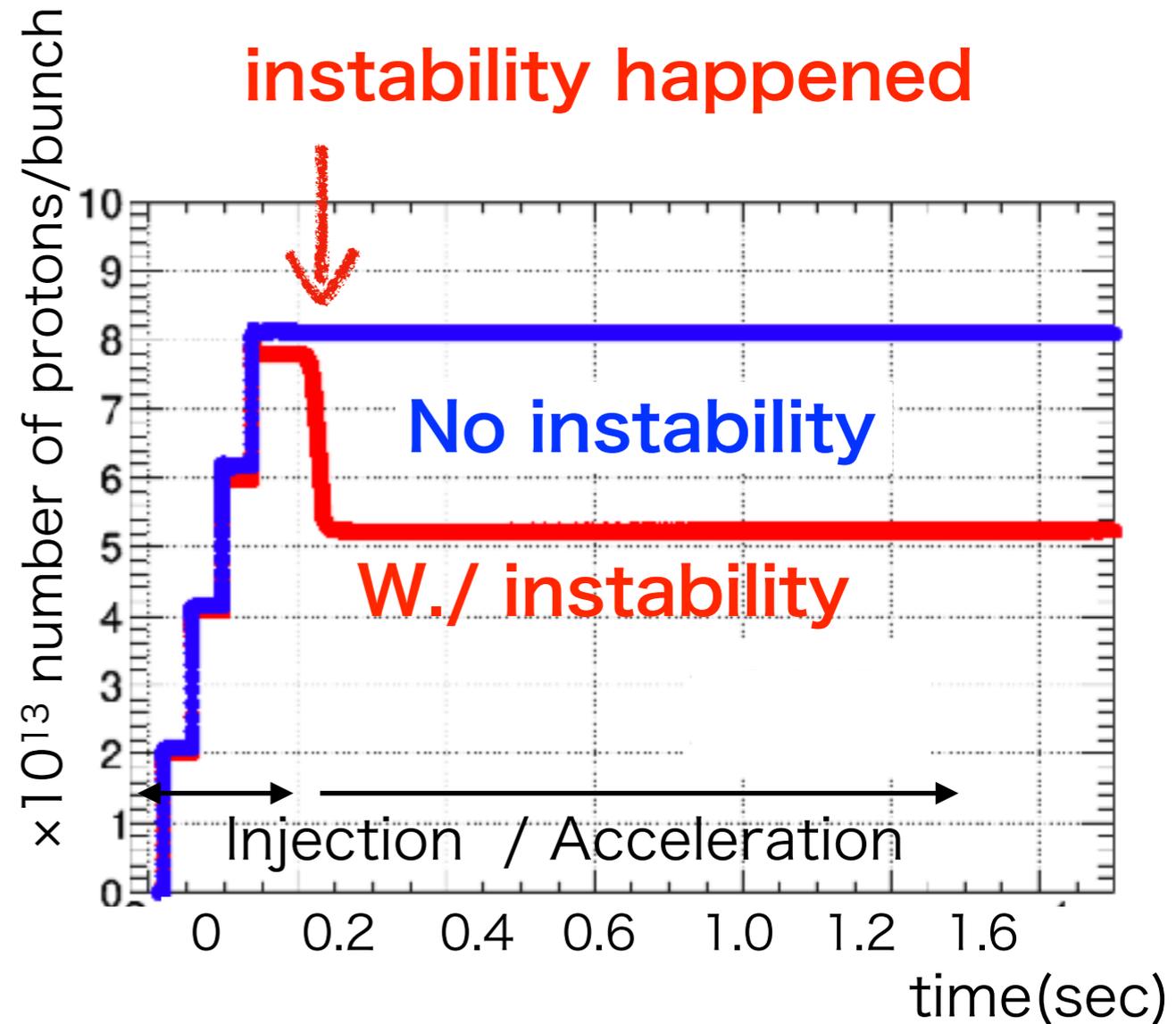
acceptable beam power loss at the MR is approximately 1 kW at present

Estimating the origin of the beam impedance is
necessary to mitigate beam power losses.

What are Betatron tunes?

Transverse motion for single particle $x(s) = \sqrt{\epsilon\beta(s)}\cos(\varphi(s) + \varphi_0)$

Betatron tune $\nu_{x,y} = \dfrac{1}{2\pi}\oint\dfrac{ds}{\beta_{x,y}(s)}$ number of transverse oscillations per turn

ν =integer ν =half integer

Figs. from S.Y. Lee

The betatron tunes under certain conditions, $k\nu_x \pm \ell\nu_y = m$, where k, l and m are integer causes beam loss.

High intensity effect (1)
Tune spread

Number of protons per beam is limited by beam loss

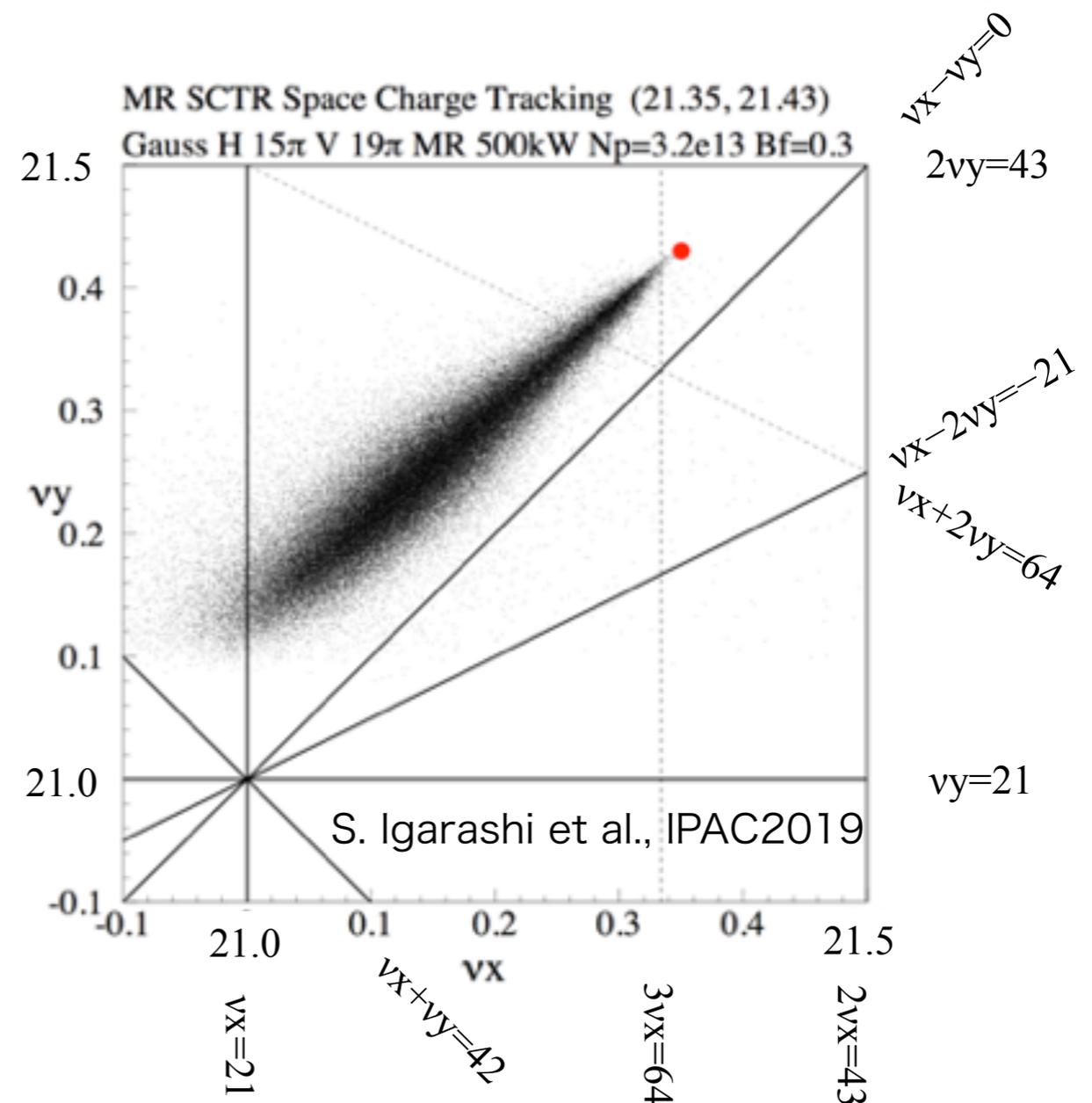Betatron tune (v_x, v_y) has a spread due to "direct and indirect space charge effect"
(approximately 0.4)

Beam loss "reduction" and "localization" are important and planning
with tune, Intra-bunch feed back, RF, Sextupoles, Trim-S, Octupoles, collimeters···.
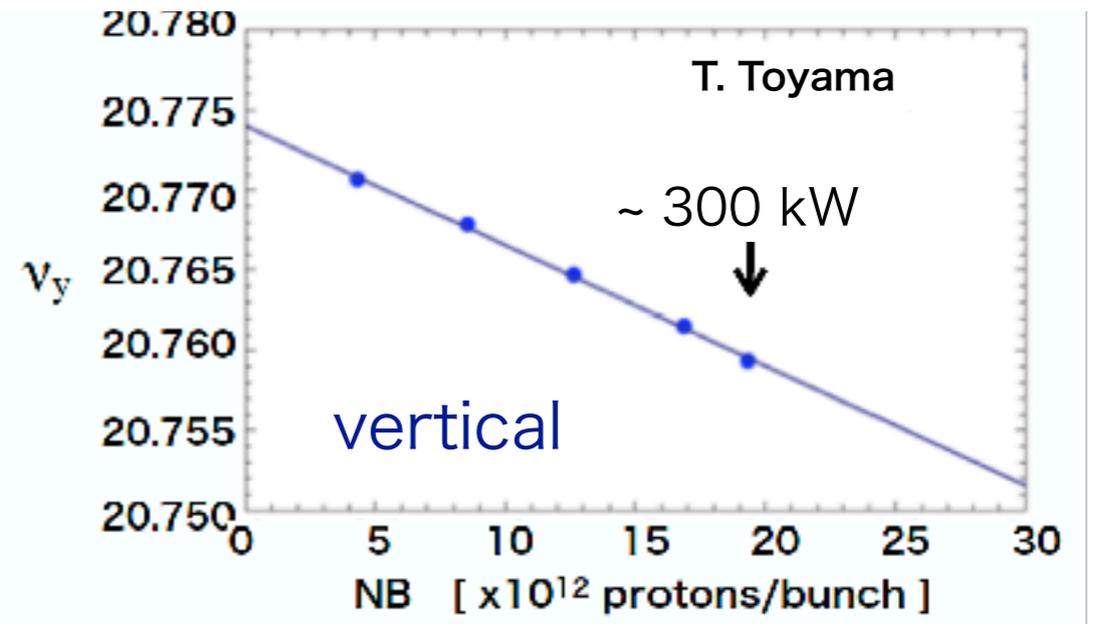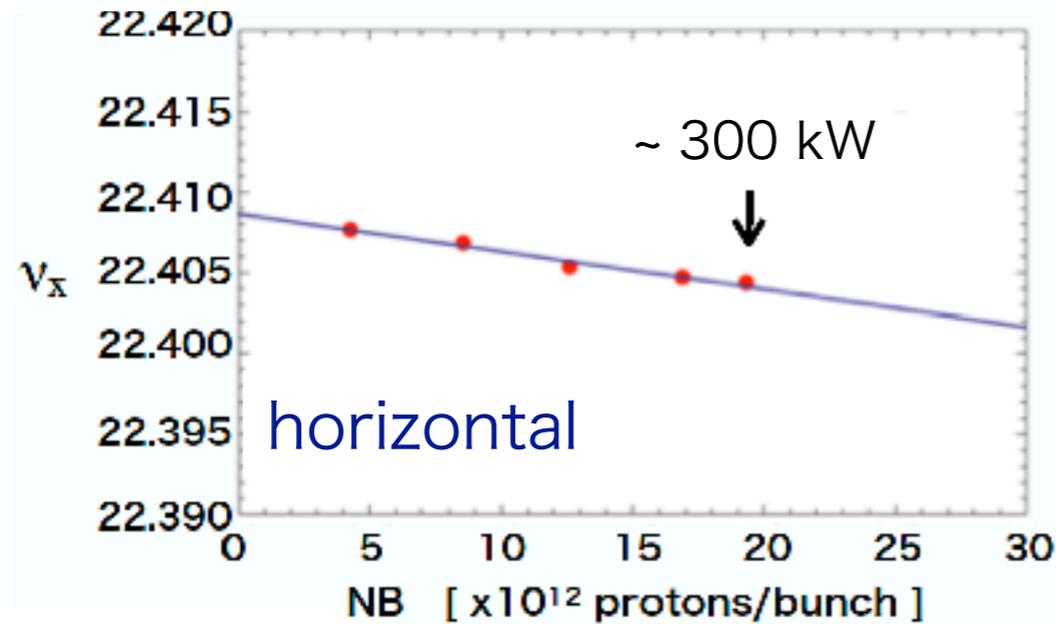
resonance lines and calculated tune spread

MR SCTR Space Charge Tracking (21.35, 21.43)
Gauss H 15π V 19π MR 500kW Np=3.2e13 Bf=0.3

S. Igarashi et al., IPAC2019

vx−vy=0
2vy=43
vx−2vy=−21
vx+2vy=64
vy=21
vx=21
vx+vy=42
3vx=64
2vx=43

Coherent tune shift

Single bunch event measurements (Dec. 2015)

$$\Delta\nu_{x,y} = -\frac{q^2 N_b R}{8\pi^{3/2}\nu_{x,y}^0 \beta^2 E\sigma_b} Im\left(Z_{x,y}^{eff}\right) \cdot f$$

~ 300 kW

horizontal

ν_x

22.420
22.415
22.410
22.405
22.400
22.395
22.390

0   5   10   15   20   25   30

NB [x10^{12} protons/bunch]

T. Toyama

~ 300 kW

vertical

ν_y

20.780
20.775
20.770
20.765
20.760
20.755
20.750

0   5   10   15   20   25   30

NB [x10^{12} protons/bunch]

To observe the tune shift due to the space charge, the intensity dependence has been measured first.

Coherent tune shift

Single bunch event measurements (Dec. 2015)

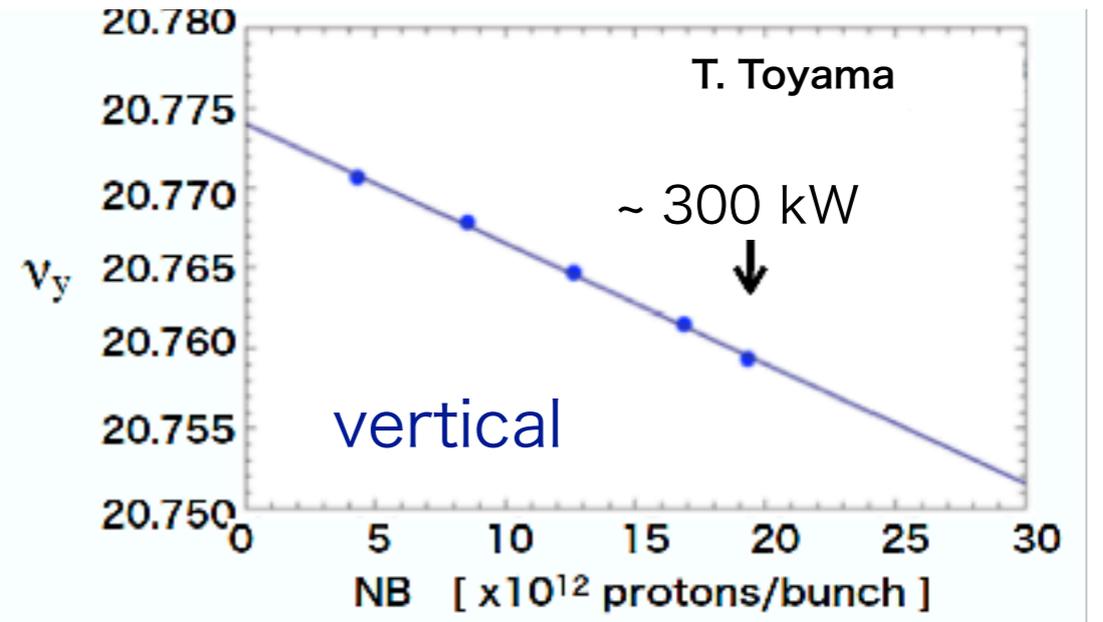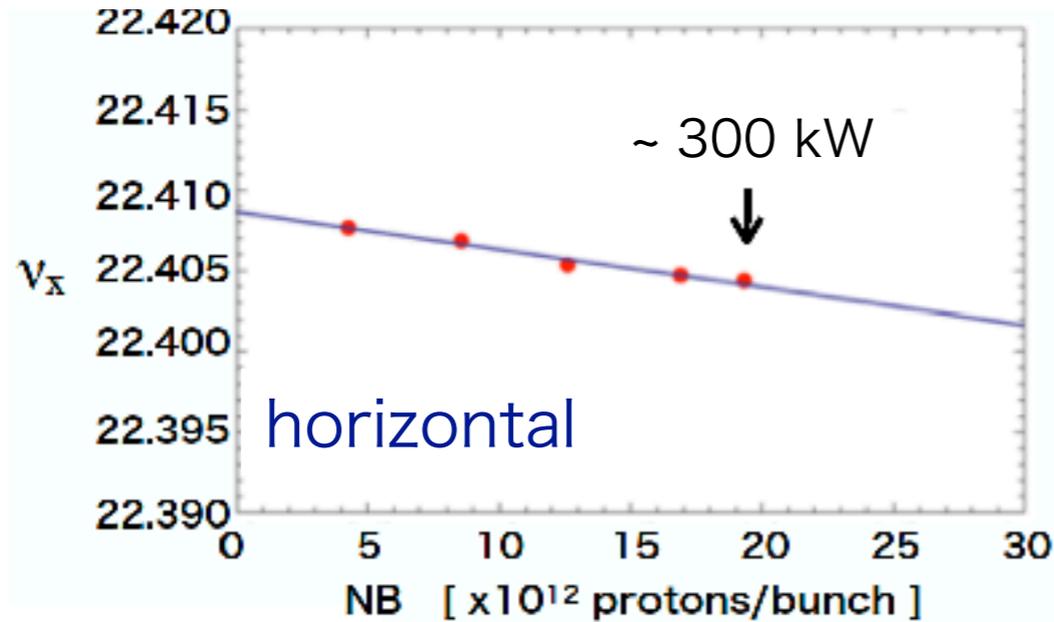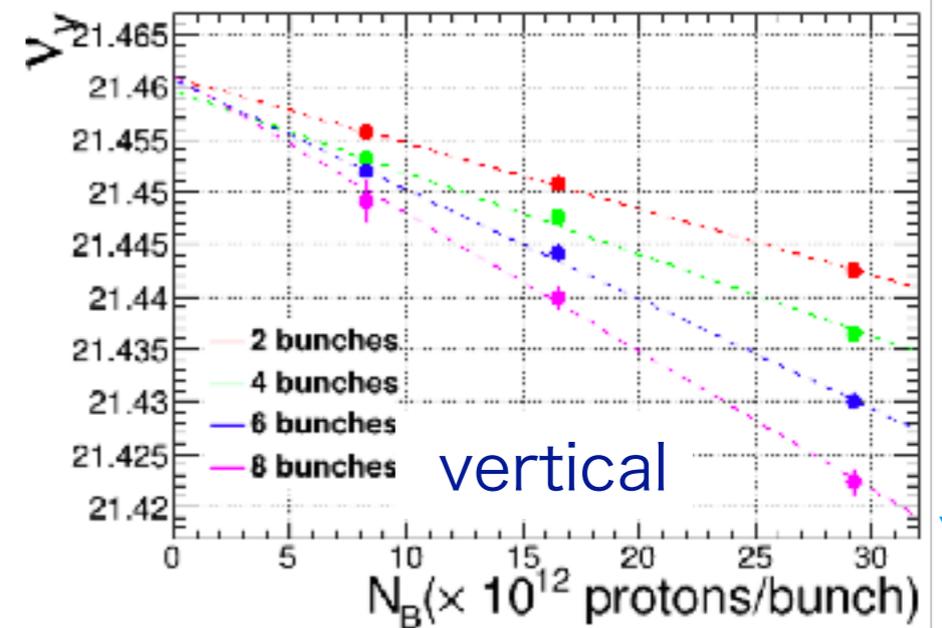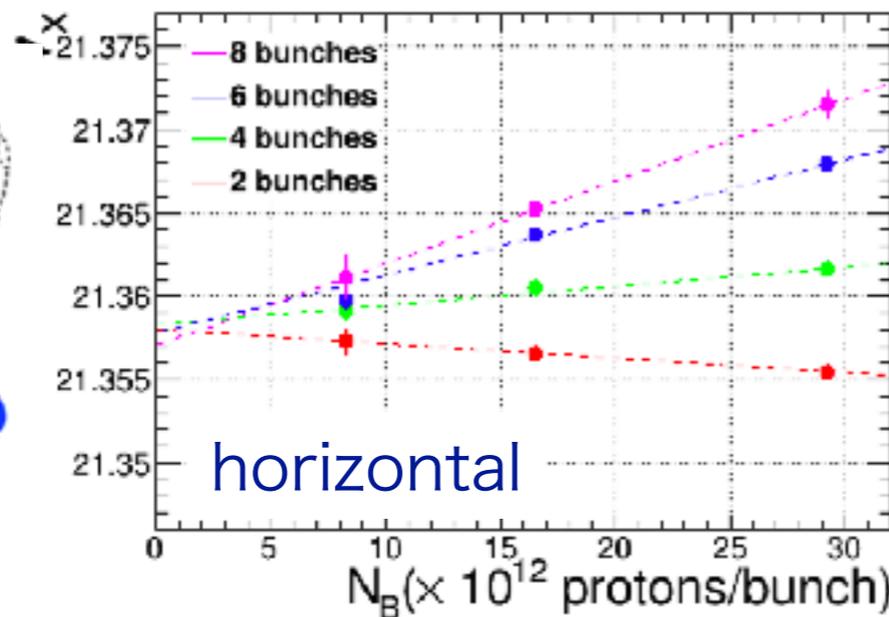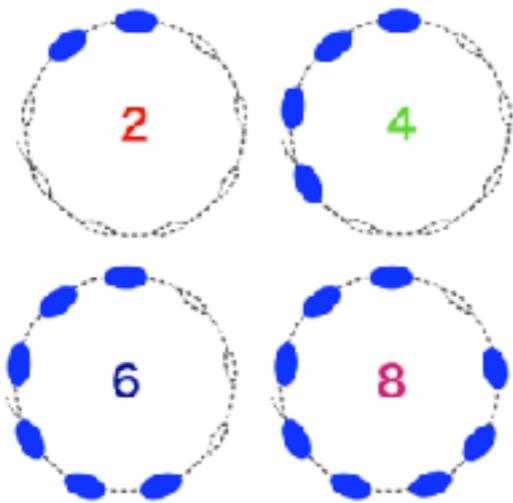$$\Delta \nu_{x,y} = -\frac{q^2 N_b R}{8\pi^{3/2}\nu_{x,y}^0 \beta^2 E \sigma_b} Im\left(Z_{x,y}^{eff}\right) \cdot f$$

~ 300 kW

horizontal

ν_x

NB [x10^{12} protons/bunch]

T. Toyama

~ 300 kW

vertical

ν_y

NB [x10^{12} protons/bunch]

Multi bunch event measurements (Nov. 2017)

8 bunches
6 bunches
4 bunches
2 bunches

horizontal

N_B(× 10^{12} protons/bunch)

2 bunches
4 bunches
6 bunches
8 bunches
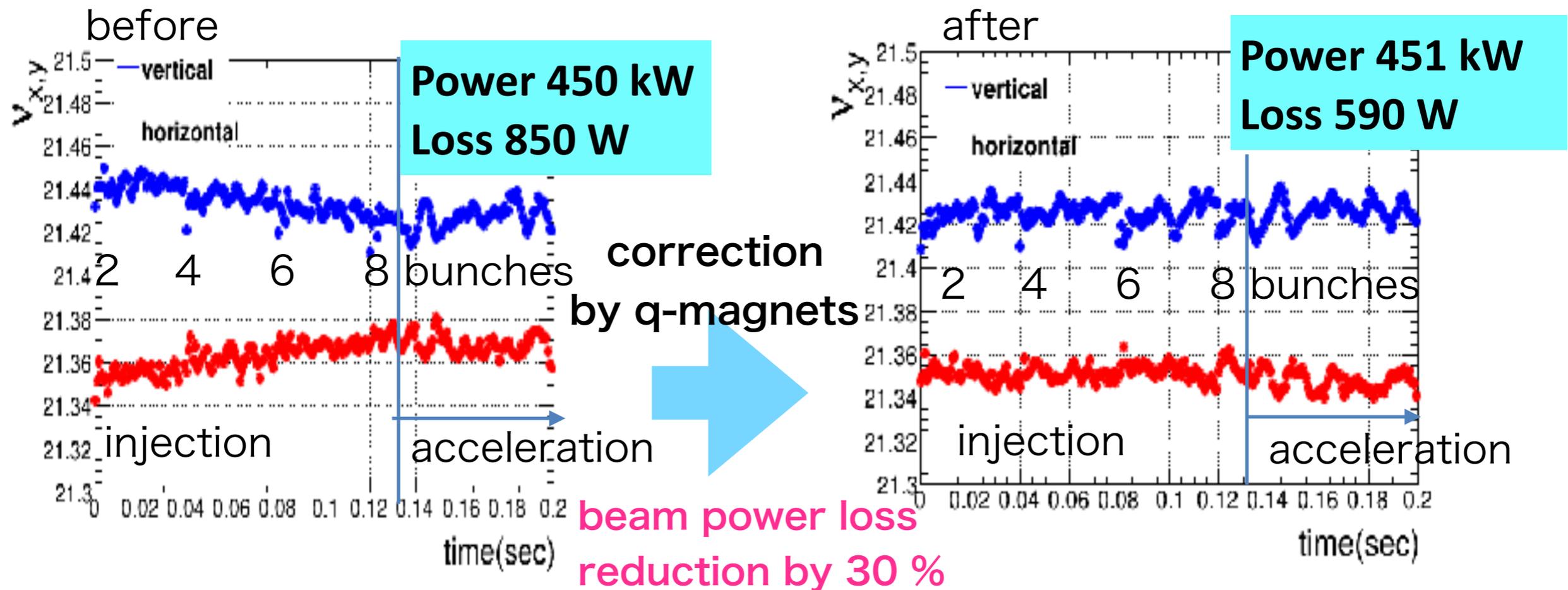
vertical

N_B(× 10^{12} protons/bunch)

Different behaviour between single bunch and multi bunches were observed.

Tune shift correction

RCS   MR

2 bunches × 4 times injections

One of necessary element for higher beam power

before

**Power 450 kW
Loss 850 W**

2   4   6   8 bunches

injection   acceleration

time(sec)

**correction
by q-magnets**

after

**Power 451 kW
Loss 590 W**

2   4   6   8 bunches

injection   acceleration

time(sec)

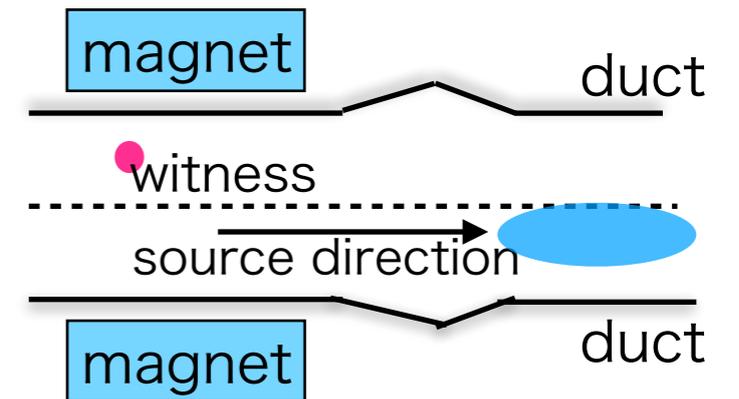beam power loss
reduction by 30 %

- Correct value for further beam intensity upgrade is predicable
- Fine tuning by the magnet system and beam monitoring system are necessary (upgrade is on-going)

collaborated with MR monitor, beam comm. and magnet groups

Origins of the tune shift

$$\Delta \nu = \boxed{\Delta \nu_{\text{space charge}}} + \Delta \nu_{\text{resistive wall}} + \Delta \nu_{\text{others}}$$

Indirect space charge effects induced by mirror image of electro-magnetic forces defined by the geometry (duct, magnet,···) and the beam
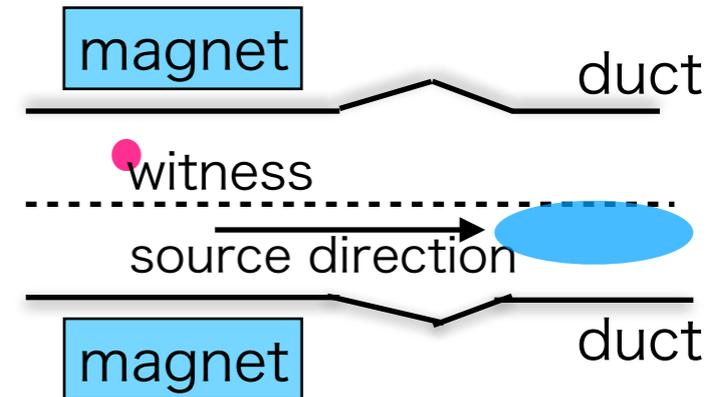
Laslet, 1963

Origins of the tune shift

$$\Delta \nu = \boxed{\Delta \nu_{\text{space charge}}} + \boxed{\Delta \nu_{\text{resistive wall}}} + \Delta \nu_{\text{others}}$$

Indirect space charge effects induced by mirror image of electro-magnetic forces defined by the geometry (duct, magnet,···) and the beam
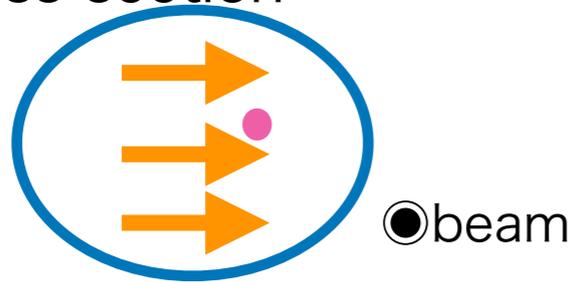
Laslet, 1963

magnet — duct
• witness
source direction
magnet — duct

Resistive wall effects by the duct material and cross-section geometry

dipole wake

Chao et al., Phys. Rev. A. B. 5, 111001, 2002
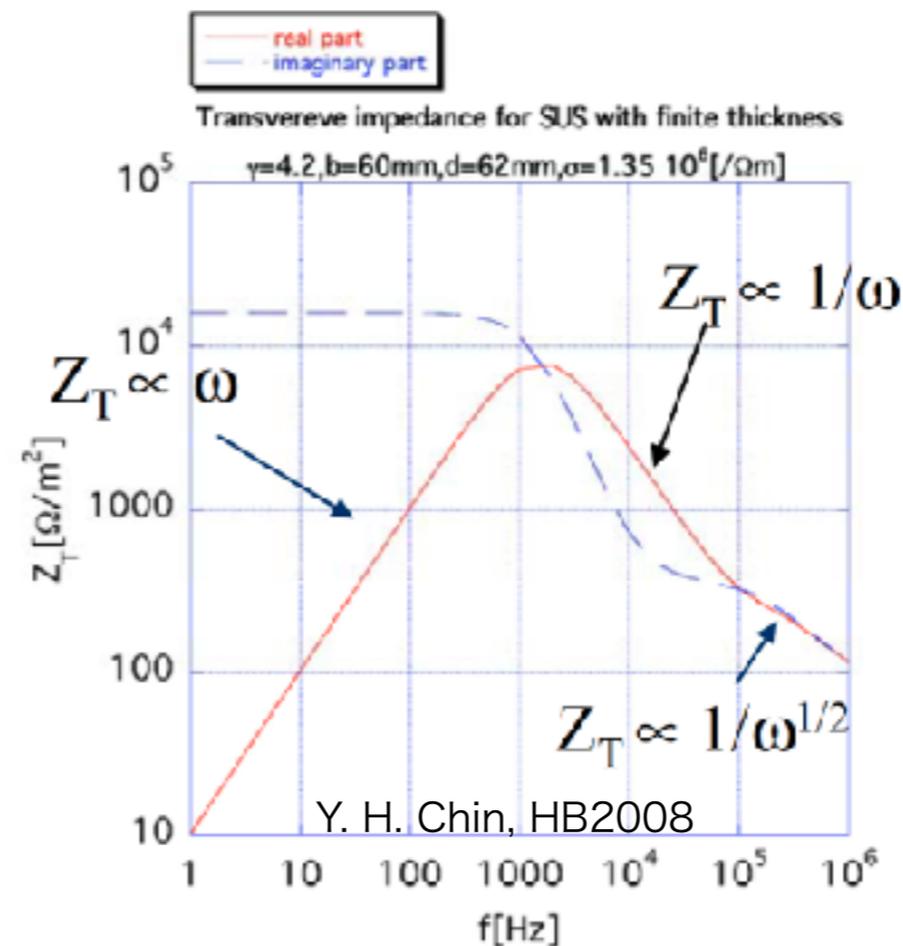Shobuda et al., Phys. Rev. E 66, 056501, 2002

duct cross-section

◉beam

quadrupolar wake field

asymmetry for horizontal and vertical

defocus
focus

effective especially for multi-bunch

Transvereve impedance for SUS with finite thickness
$\gamma=4.2, b=60mm, d=62mm, \sigma=1.35 \ 10^6 [/\Omega m]$

real part
imaginary part

$Z_T \propto 1/\omega$

$Z_T \propto \omega$

$Z_T \propto 1/\omega^{1/2}$

$Z_T [\Omega/m^2]$

f[Hz]

Y. H. Chin, HB2008

Origins of the tune shift

$$\Delta \nu = \boxed{\Delta \nu_{\text{space charge}}} + \boxed{\Delta \nu_{\text{resistive wall}}} + \boxed{\Delta \nu_{\text{others}}}$$
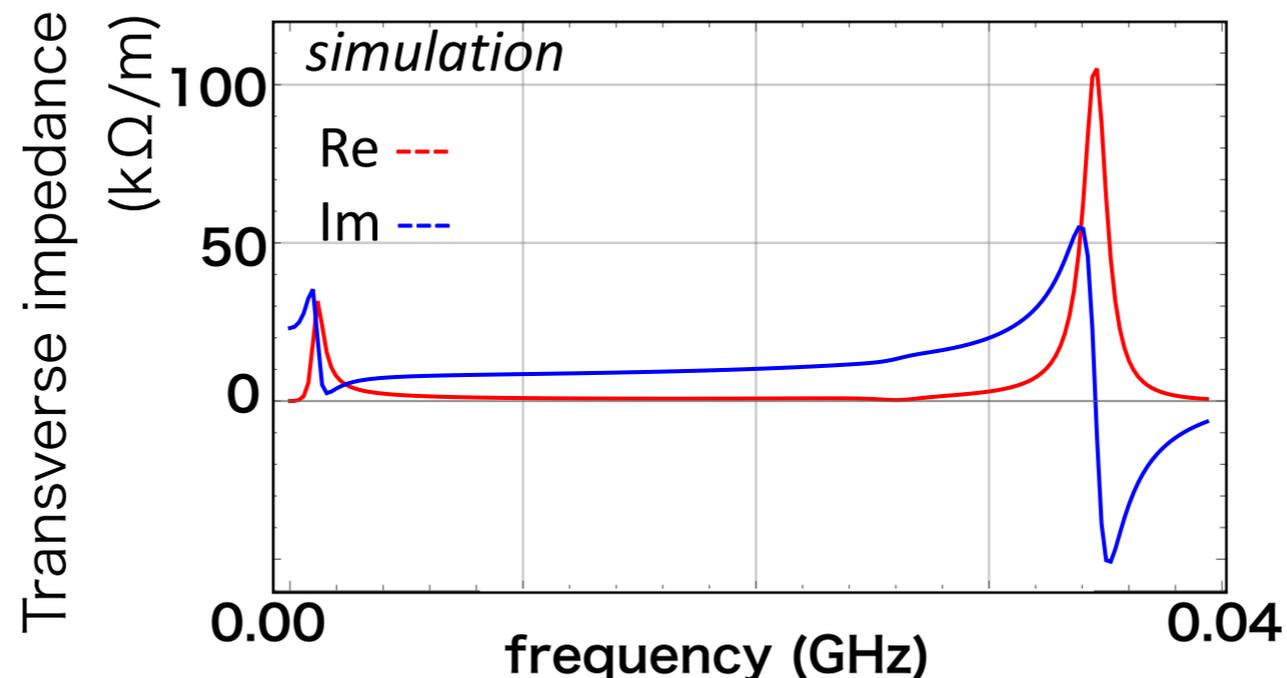
Indirect space charge effects induced by mirror image of electro-magnetic forces defined by the geometry (duct, magnet,···) and the beam

Laslet, 1963
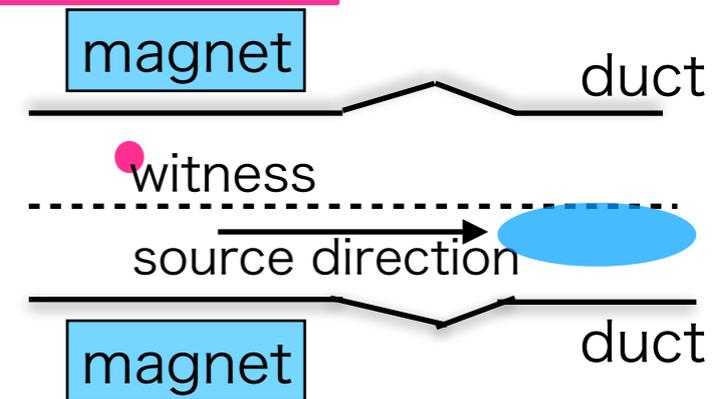
Resistive wall effects by the duct material and cross-section geometry
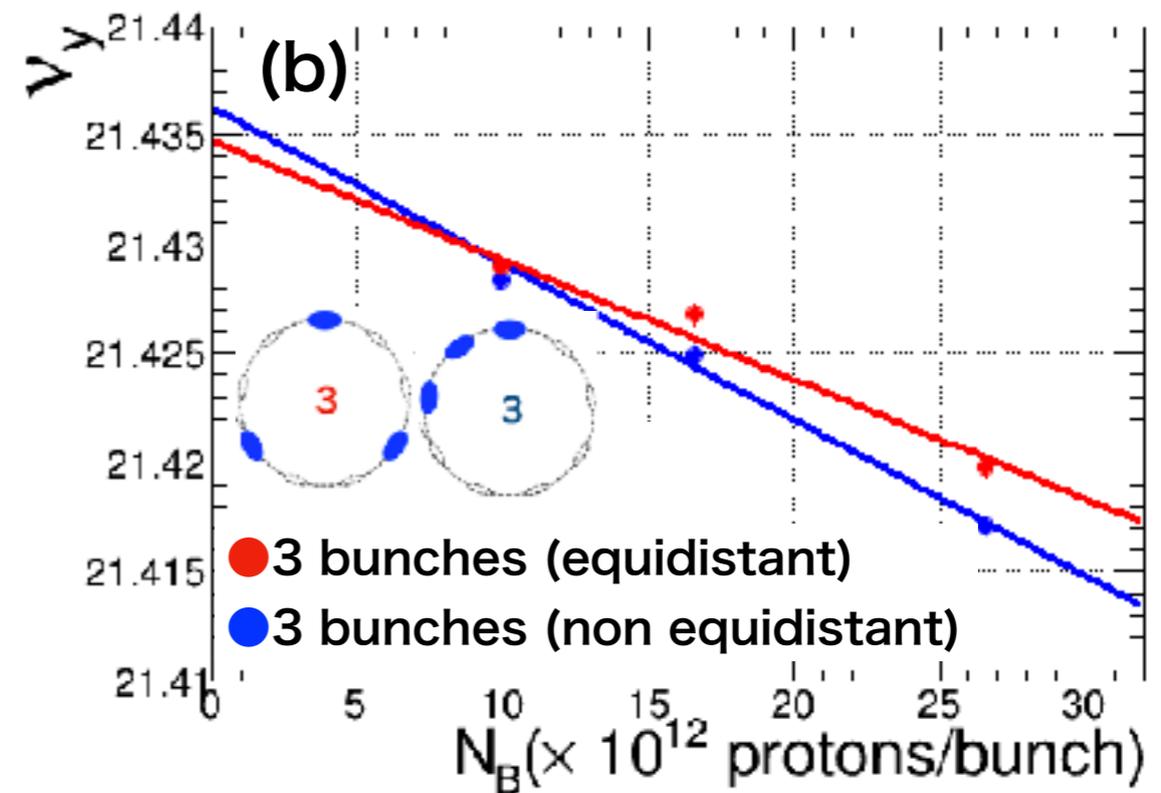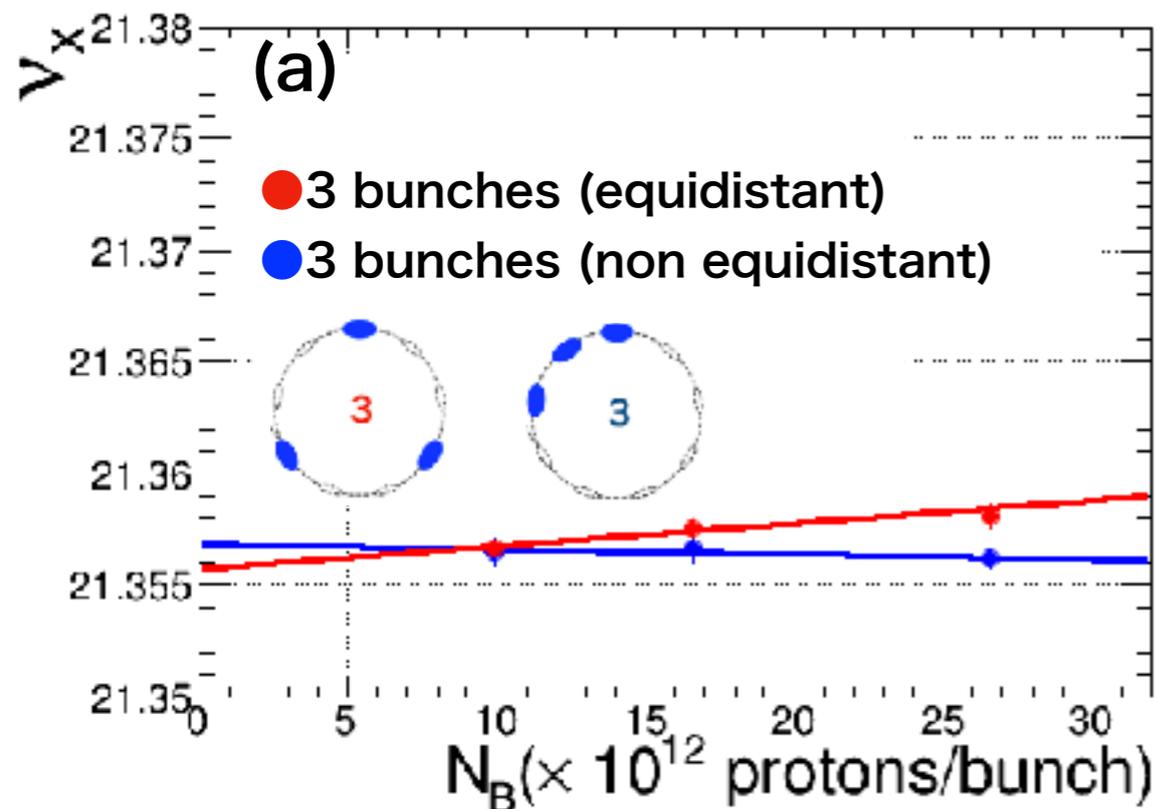
Other impedance sources, kickers,···

Qualitative understandings by theories have done.

Bunch filling pattern?

Correction values of tunes can be estimated from measured results and theories.

The model for explanation of the bunch filling pattern dependence is needed.

Impedance model reconstruction of the MR is necessary to future high intensity beam.
Impedance sources and wake field evaluation are on-going.

High intensity effect (3)
Collective beam instability

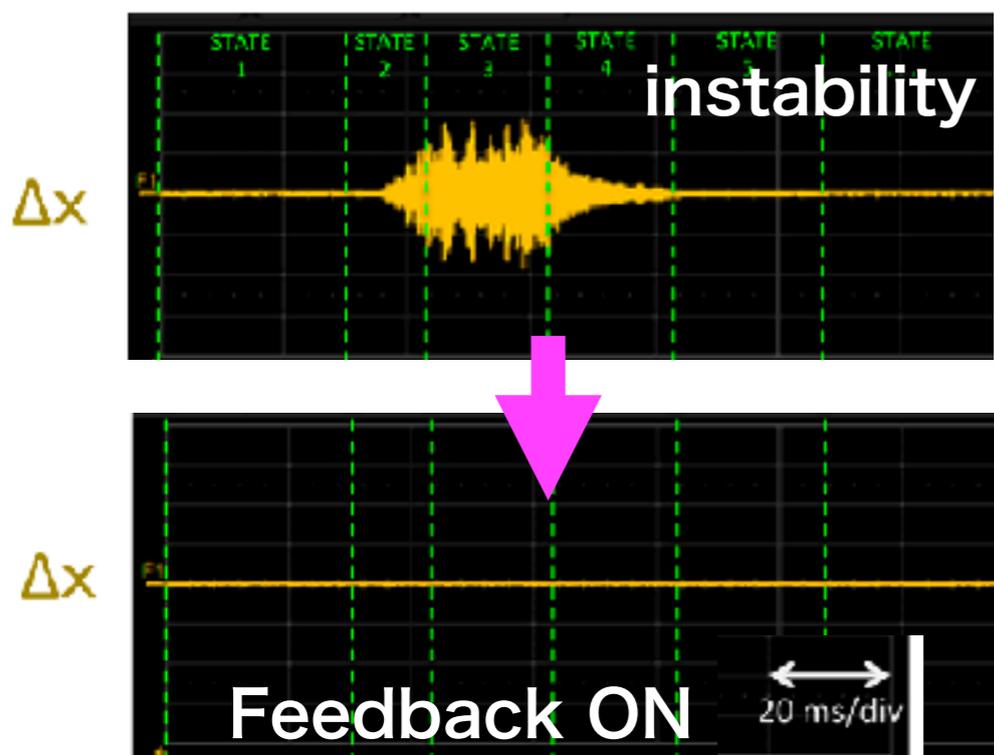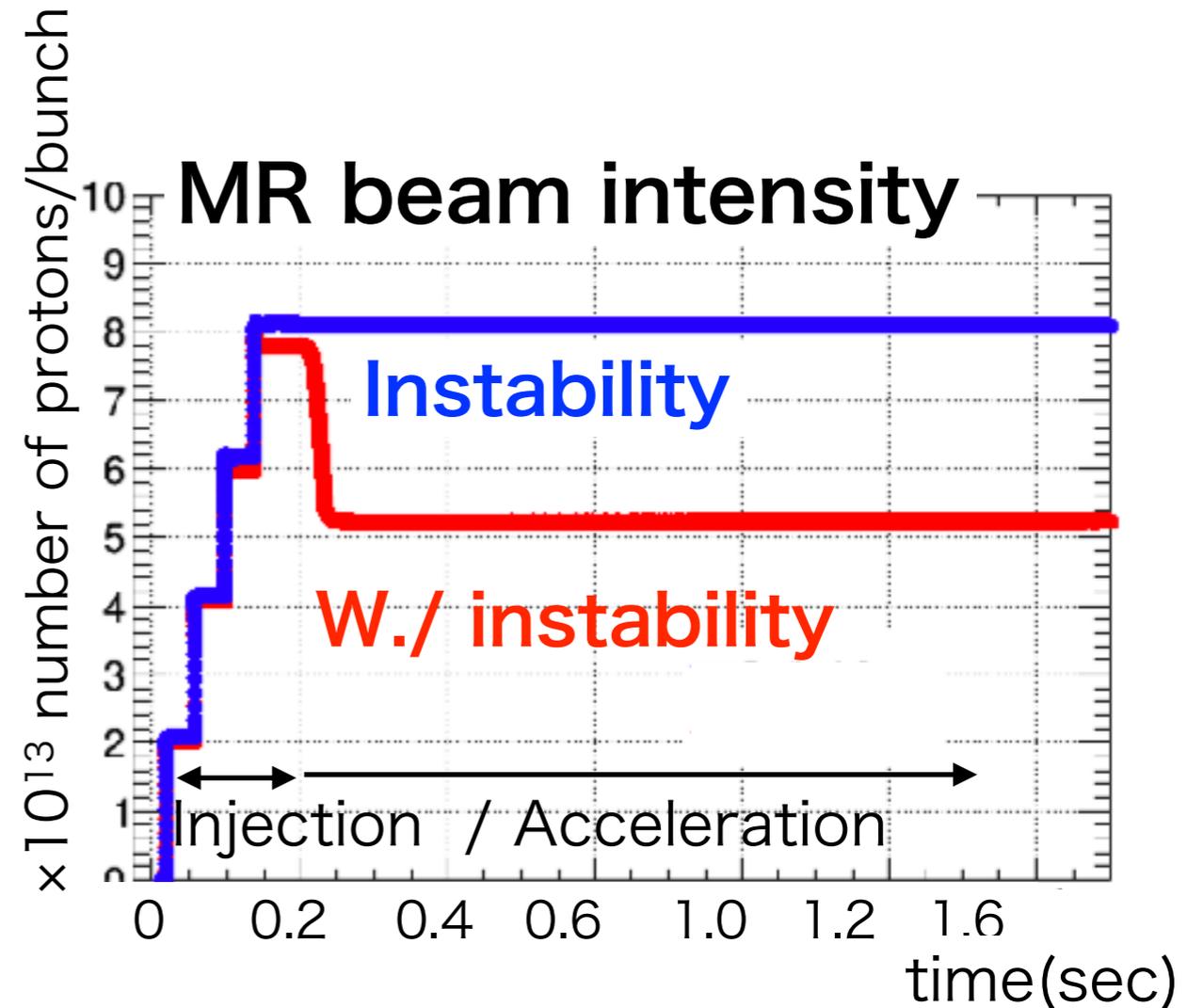Another aspect of the wake field related to the beam growth.

instability

Δx

Δx

Feedback ON   20 ms/div

Fig. from T. Toyama et al. PASJ2015

MR beam intensity

×10^{13} number of protons/bunch

Instability

W./ instability

Injection / Acceleration

0   0.2   0.4   0.6   1.0   1.2   1.6

time(sec)

The model reconstruction and study on the instability is necessary.

Summary

- The MR beam power upgrade is planning by increasing the repetition rate and reducing the beam loss.

- Estimation of intensity dependent tune shifts is necessary to mitigate the beam power loss for higher beam power operation.

- The impedances along the ring affect stable particle motion and cause beam power loss as well as the tune shift.

- Reconstruction of the impedance model is indispensable for mitigating tune-shift and for suppressing instabilities.