# Space charge induced resonances and suppression in J-PARC MR

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HB2023, Geneva, Switzerland, October 11, 2023

# Outline

1. Introduction
2. Identification of source of beam loss
3. Mechanism of beam loss
4. A new optics for reducing beam loss
5. Summary

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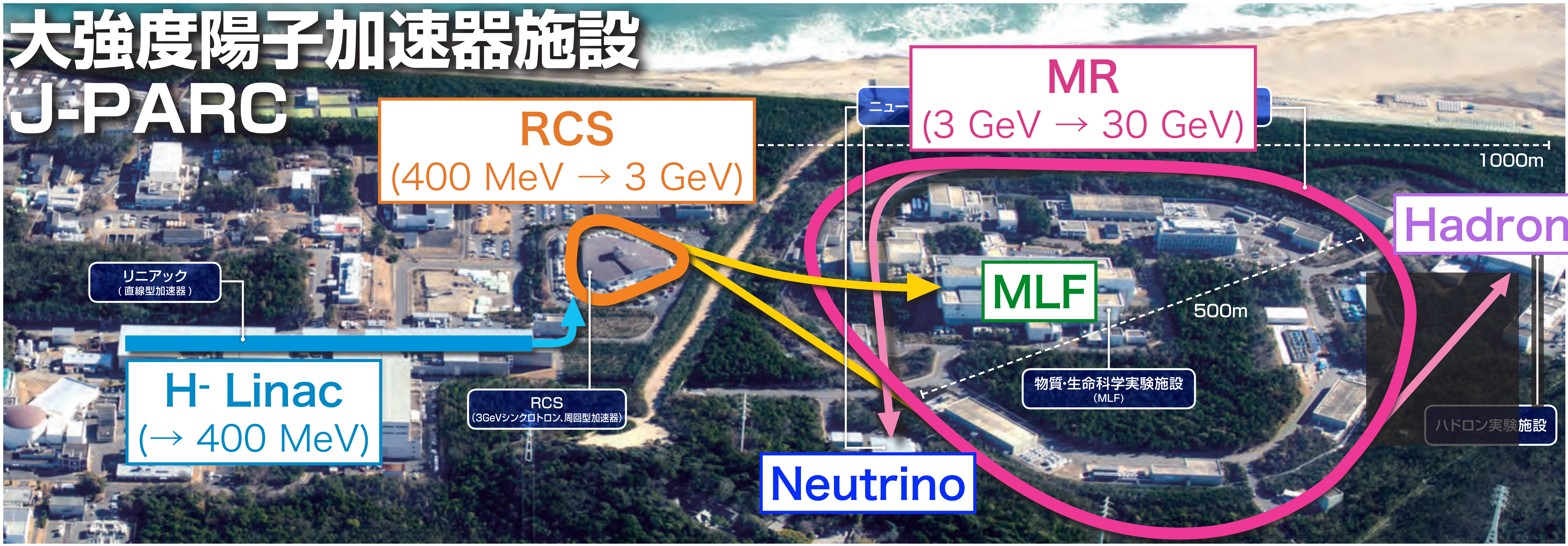
# J-PARC MR




The main ring synchrotron (MR) provides high power proton beams for the neutrino and hadron experiments.

**<u>Upgrade plan: 1.3 MW FX (fast extraction) operation</u>**

# FX beam power upgrade plan

**Power** = Energy(30 GeV) × **Number of protons** / **Cycle time**

| | | | |
|---|---|---|---|
| JFY2021 | 515 kW | $2.66\times10^{14}$ ppp | 2.48 s |
| | Long-term shutdown for faster cycling | | |
| Present | 760 kW | $2.17\times10^{14}$ ppp | 1.36 s |
| Future | 1300 kW | $3.3\times10^{14}$ ppp | 1.16 s |

ppp … protons per pulse

To increase the beam intensity, we should

- Upgrade the RF system
- **Reduce beam loss** ← **today's talk**
- Improve the localization quality of beam loss

# Strategy for beam loss reduction

Presently, beam loss is caused by

**1. Current ripples of bend power supplies**

- $\Delta x = \eta_x \frac{\Delta B}{B}, \qquad |\Delta K_1| = |K_2 \Delta x|$ T. Yasui, IPAC2023, TUXG1
Y. Sato, this meeting, MOA2I1

- We are going to reduce ripples within a year.

**2. Nonstructure resonances induced by magnet imperfections**

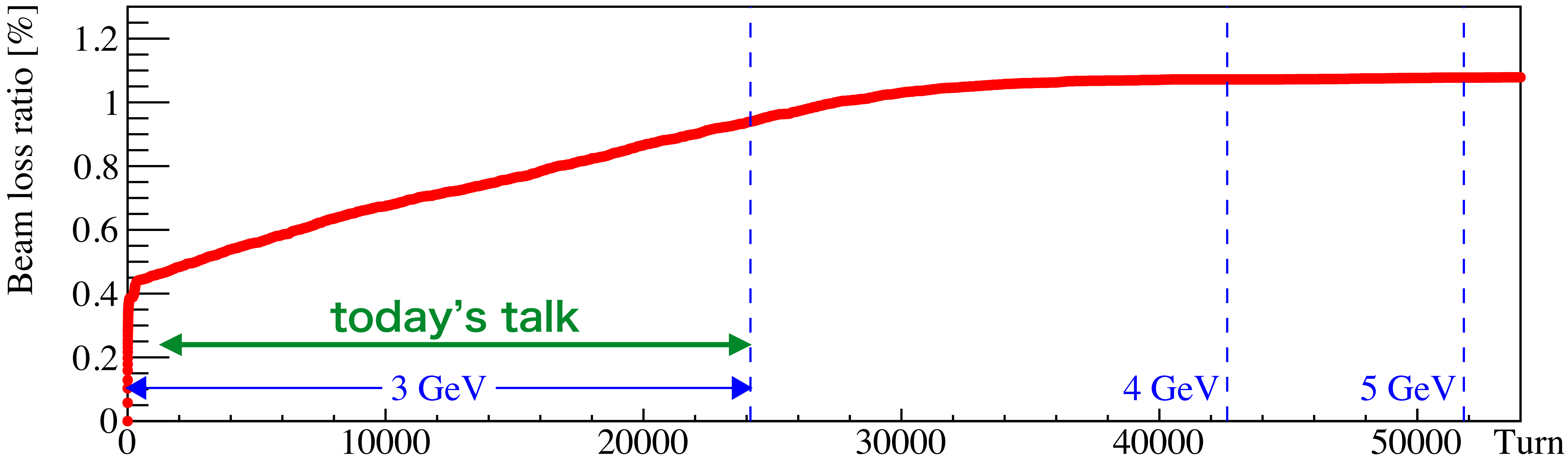
- We plan to add correction sextupole fields
H. Hotchi *et al.*, IPAC2023, TUPM055

**3. Structure resonances induced by space charge effects**

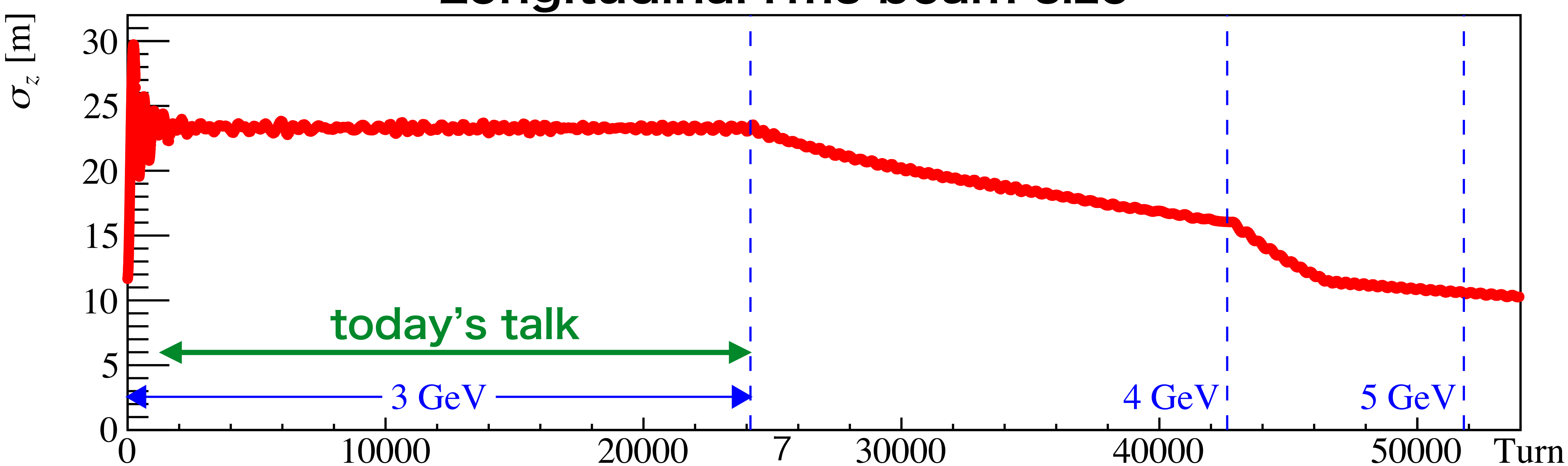
- Today’ s talk
(T. Yasui and Y. Kurimoto, PRAB **25**, 121001 (2022) + some FMA results)

# Beam loss & beam size (simulation)

## Beam loss




## Longitudinal rms beam size

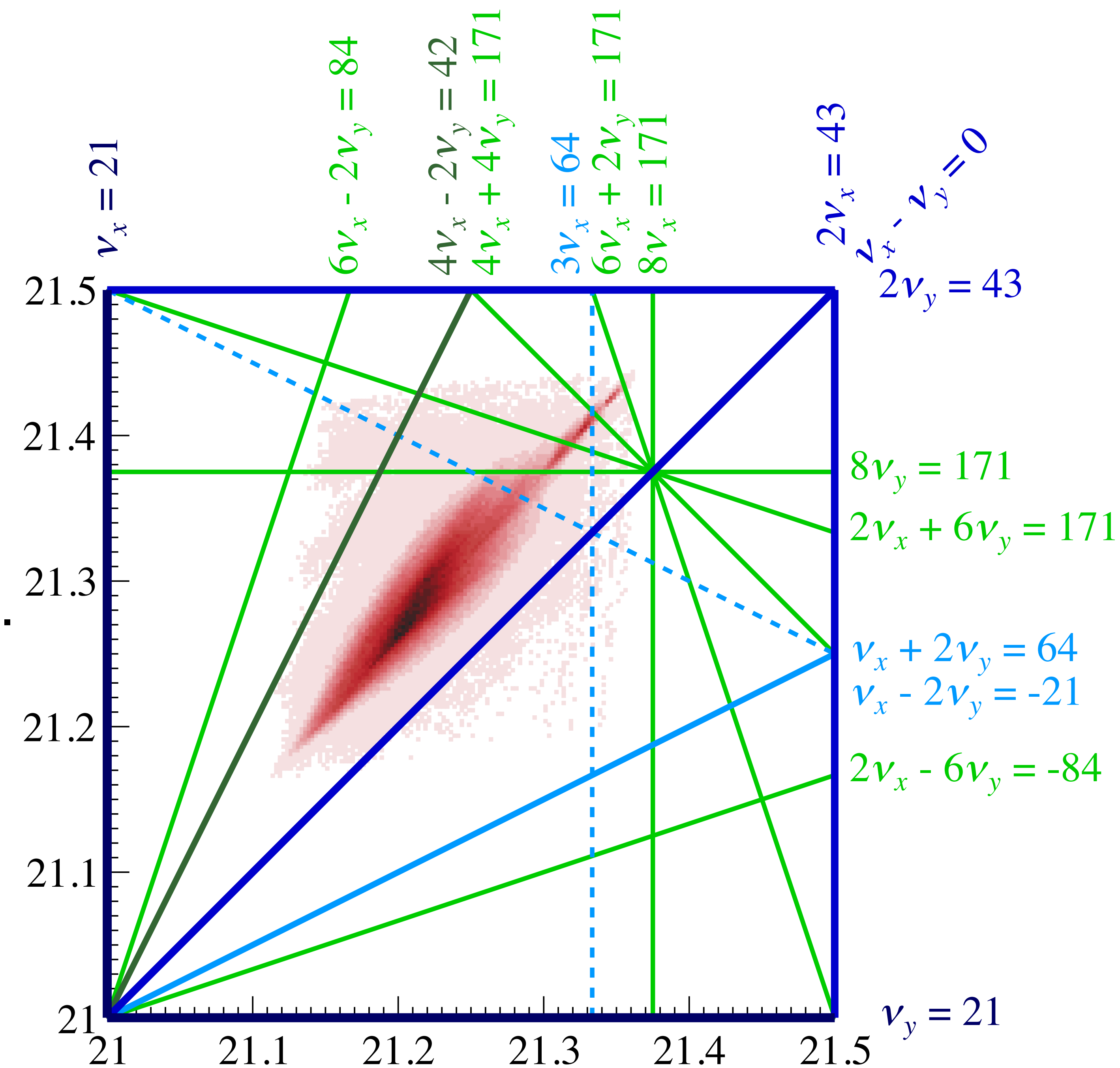


# Tune spread and resonances

The working point is set not to cross low order resonances.

Since the superperiod is only 3, it is difficult to completely avoid high order structure resonances.

The beam is crossing some 8th order structure resonances.




Beam intensity : $2.66\times10^{14}$ ppp

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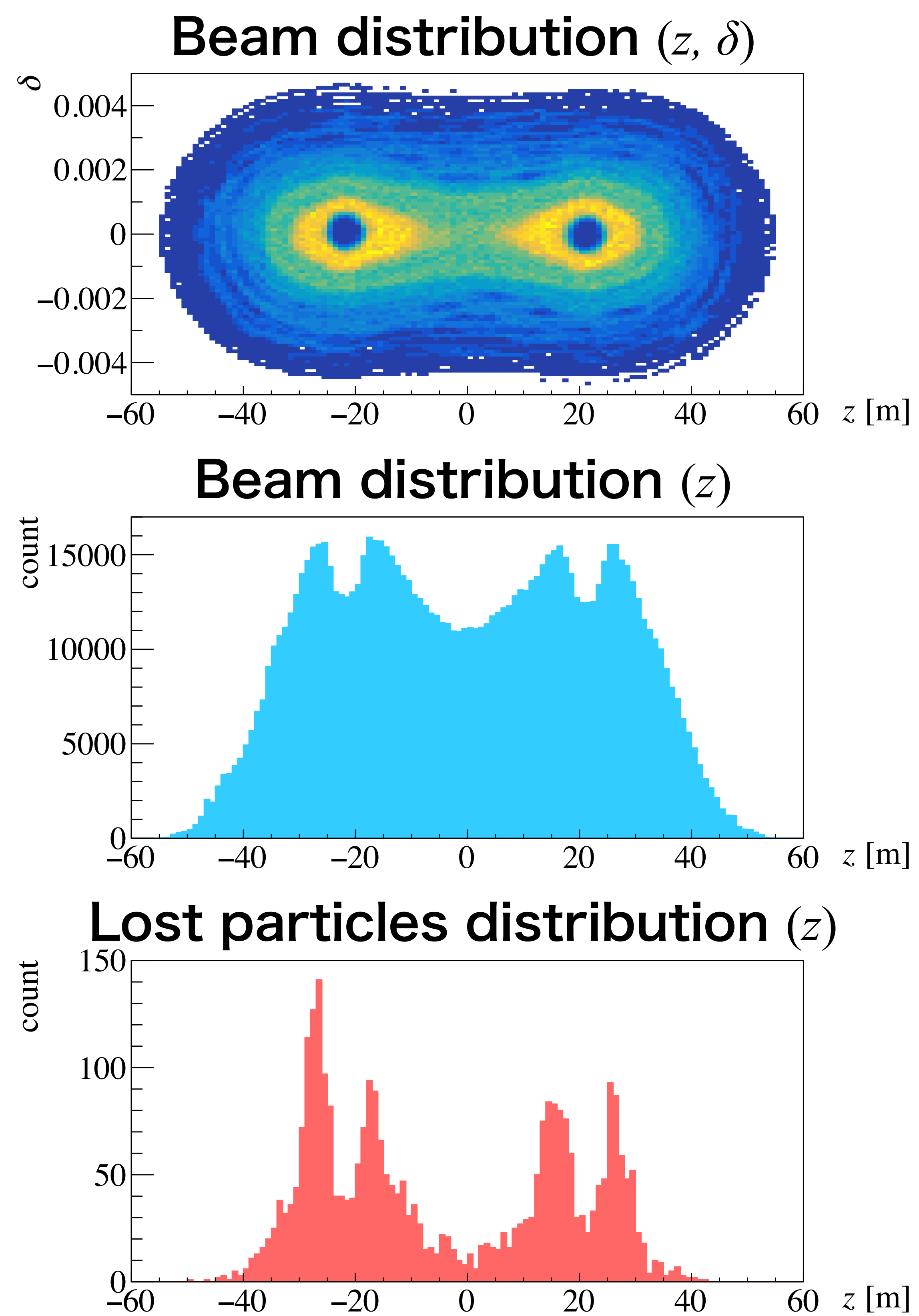
# Longitudinal distribution

2nd harmonic RF cavities are used for peak suppression.



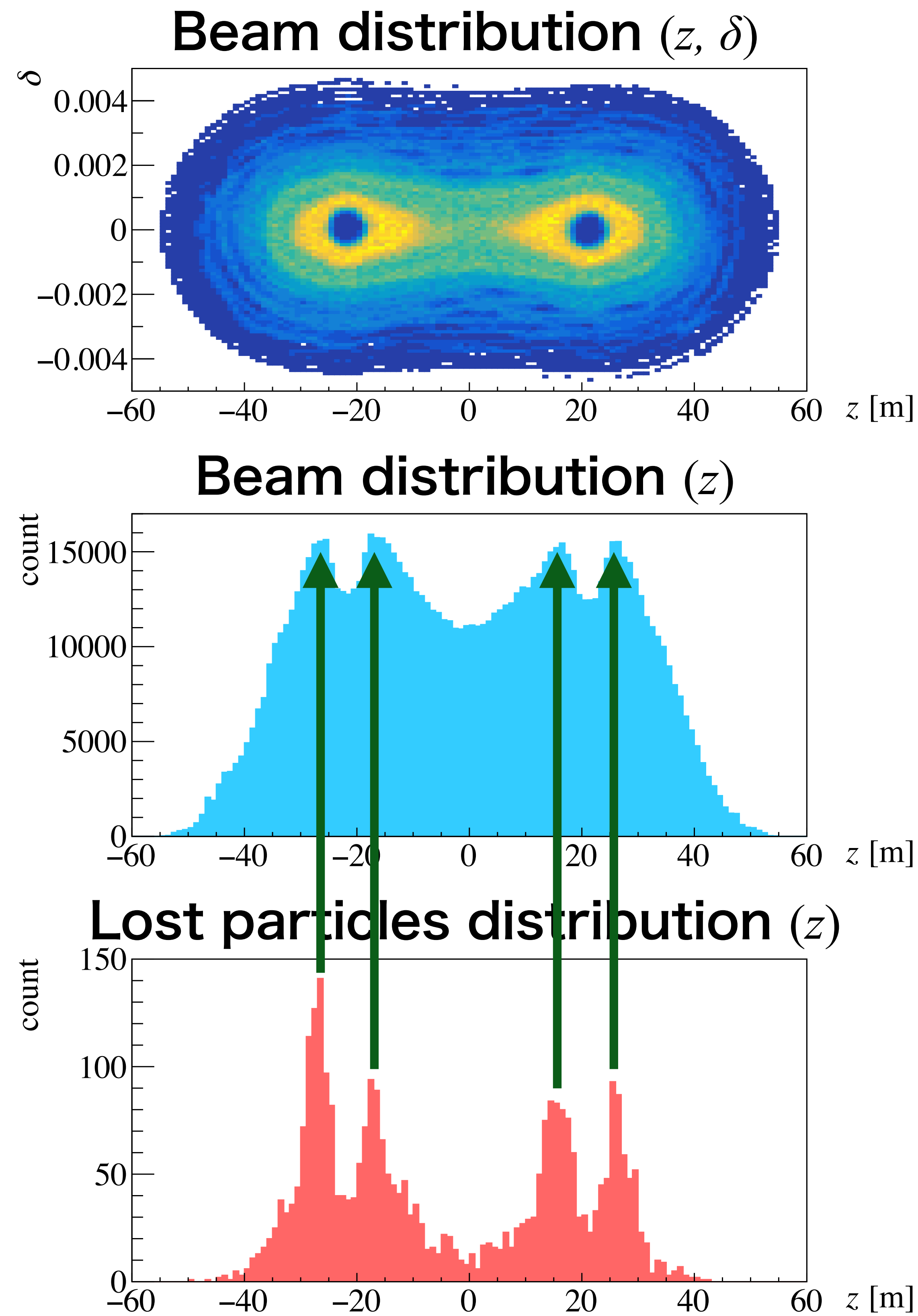
# Longitudinal distribution

2nd harmonic RF cavities are used for peak suppression.

**Most of the lost particles are found at locations of high line densities.**

Beam loss is caused by space charge effect.

Peak suppression by the 2nd harmonic RF cavities are very important.

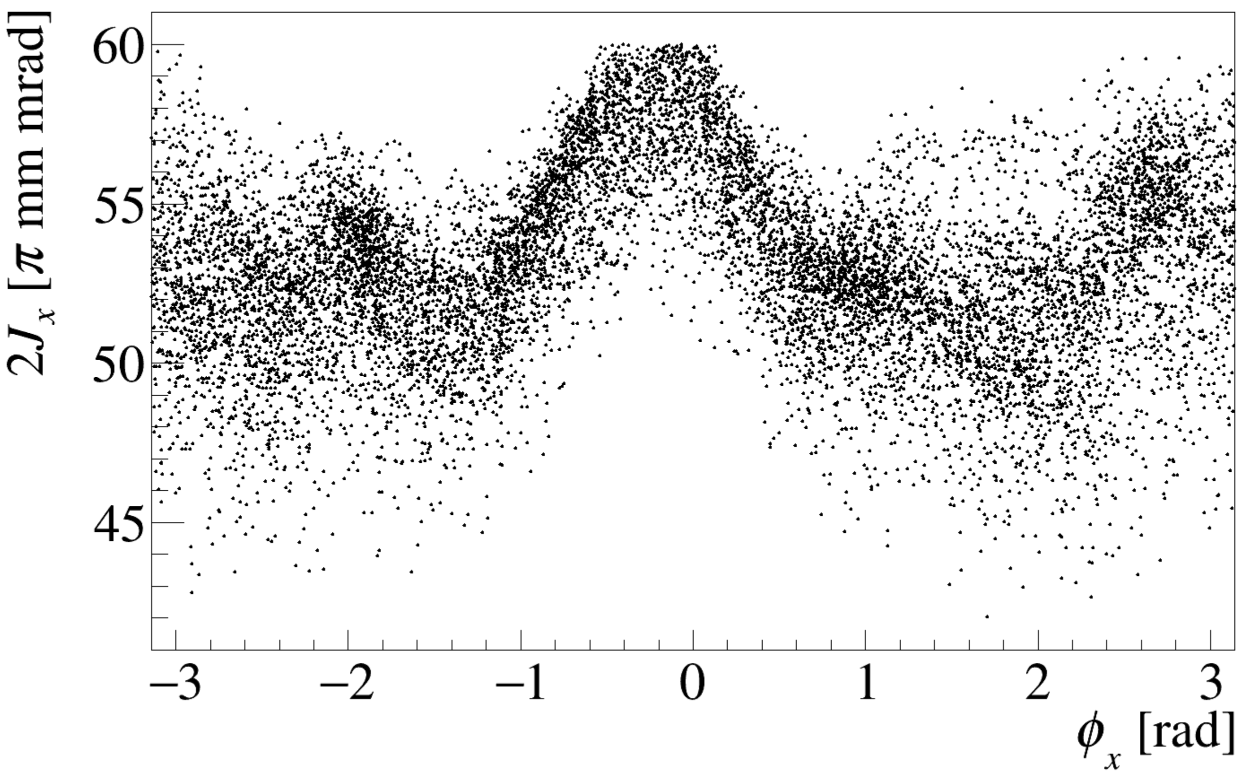


# Transverse distribution

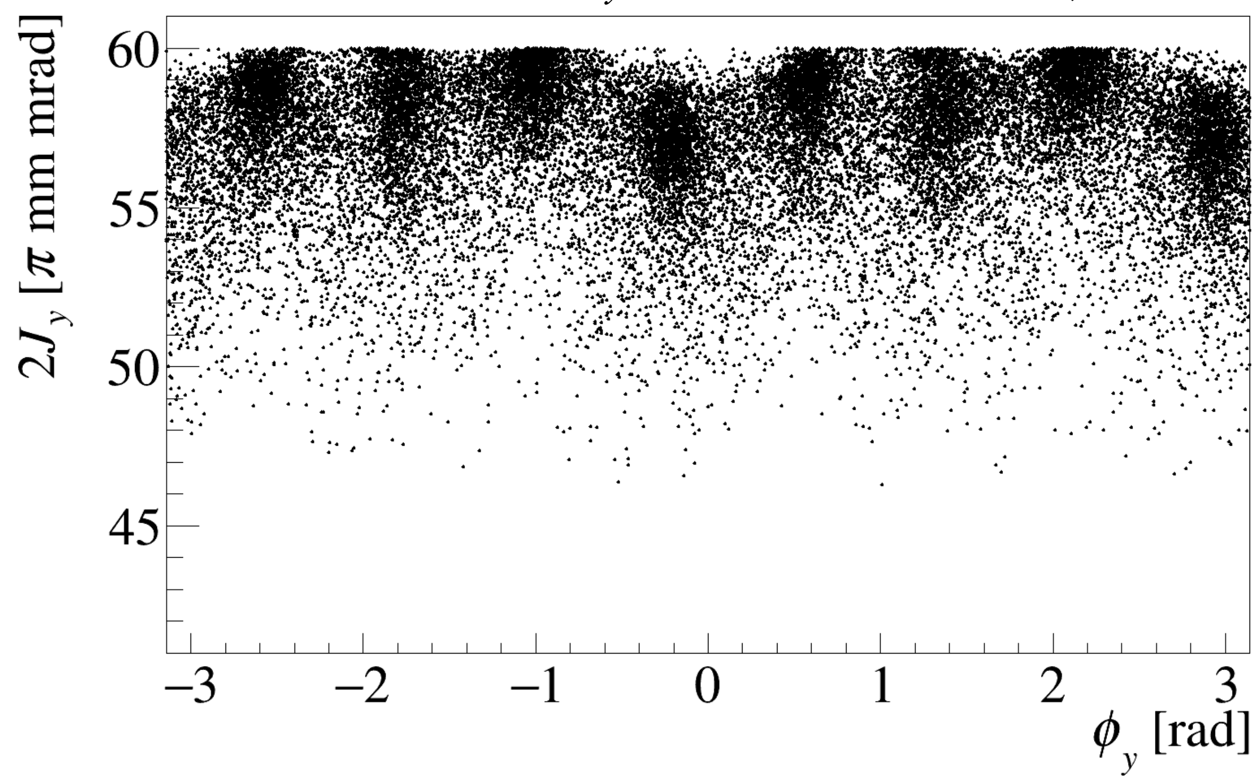
The collimators were set to $(2J_x, 2J_y) = (60\pi, 60\pi)$ mm mrad.

**Phase-space (action-angle) distribution of lost particles**

Lost because $2J_x > 60\pi$ mm mrad (28.6%)




Lost because $2J_y > 60\pi$ mm mrad (71.4%)



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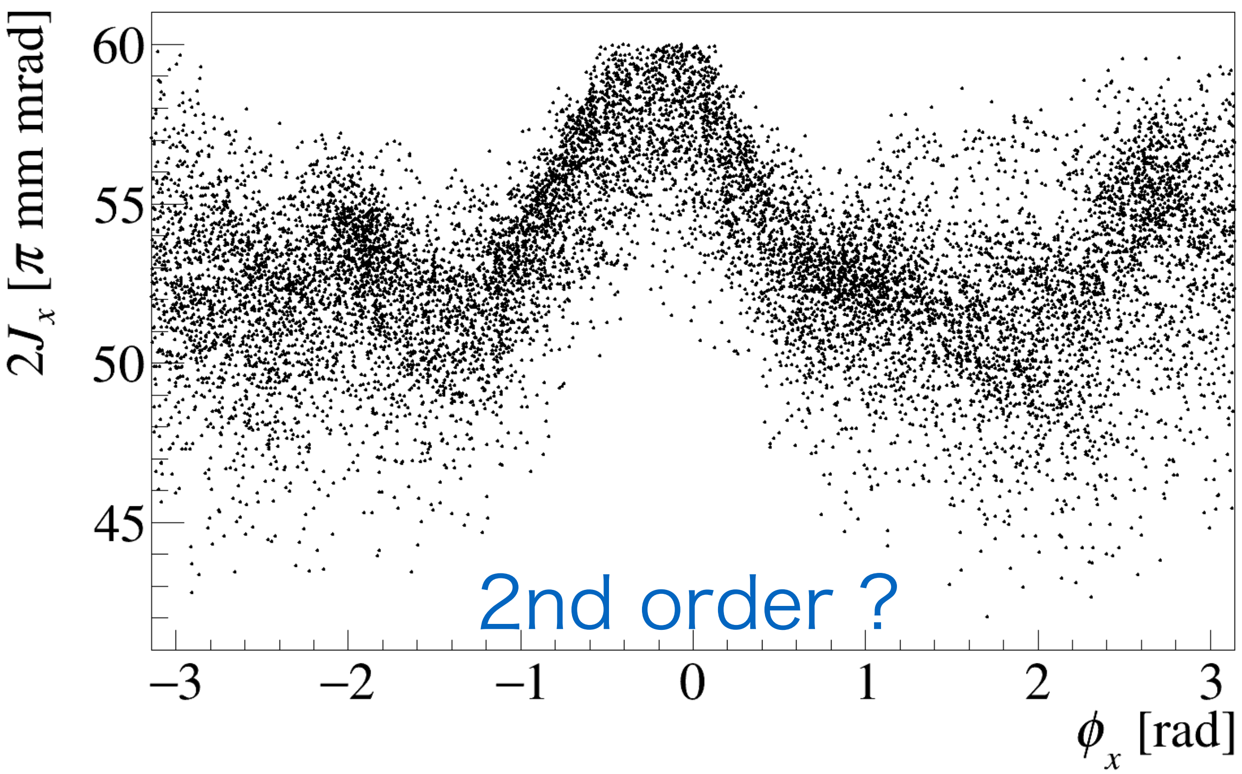


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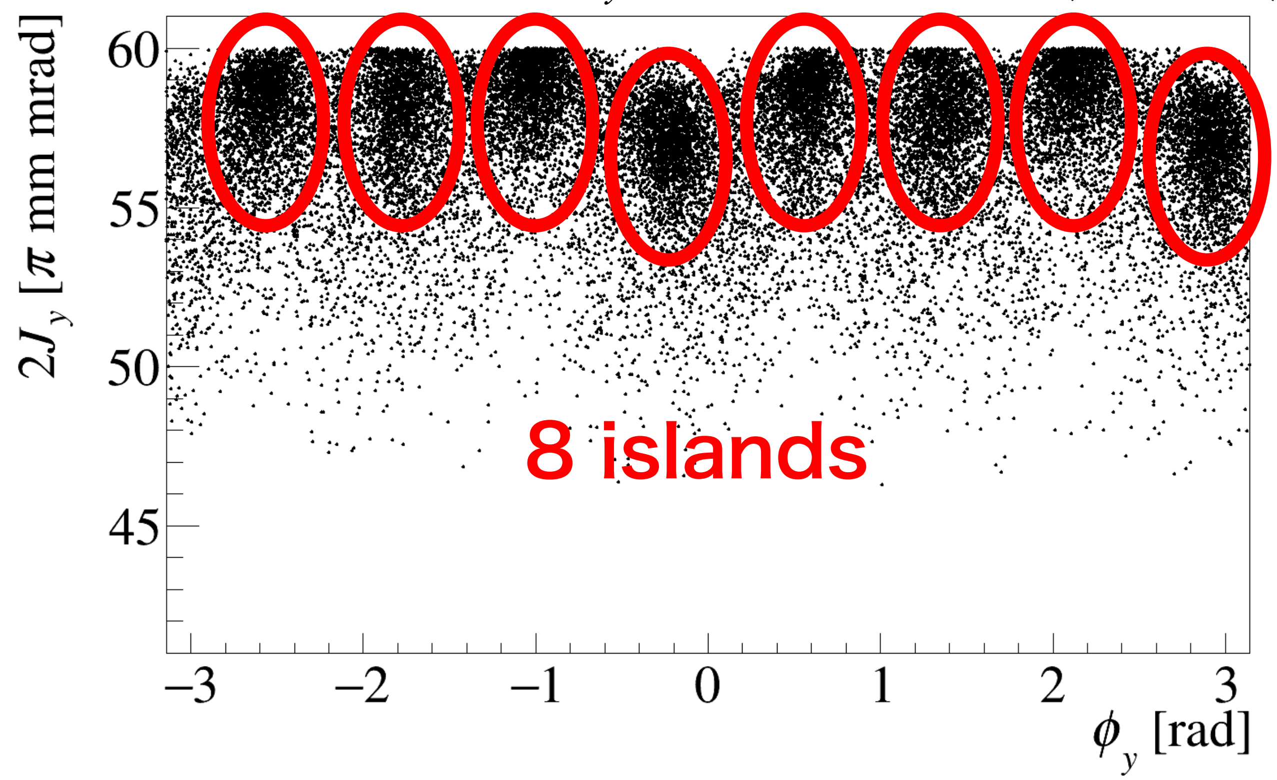
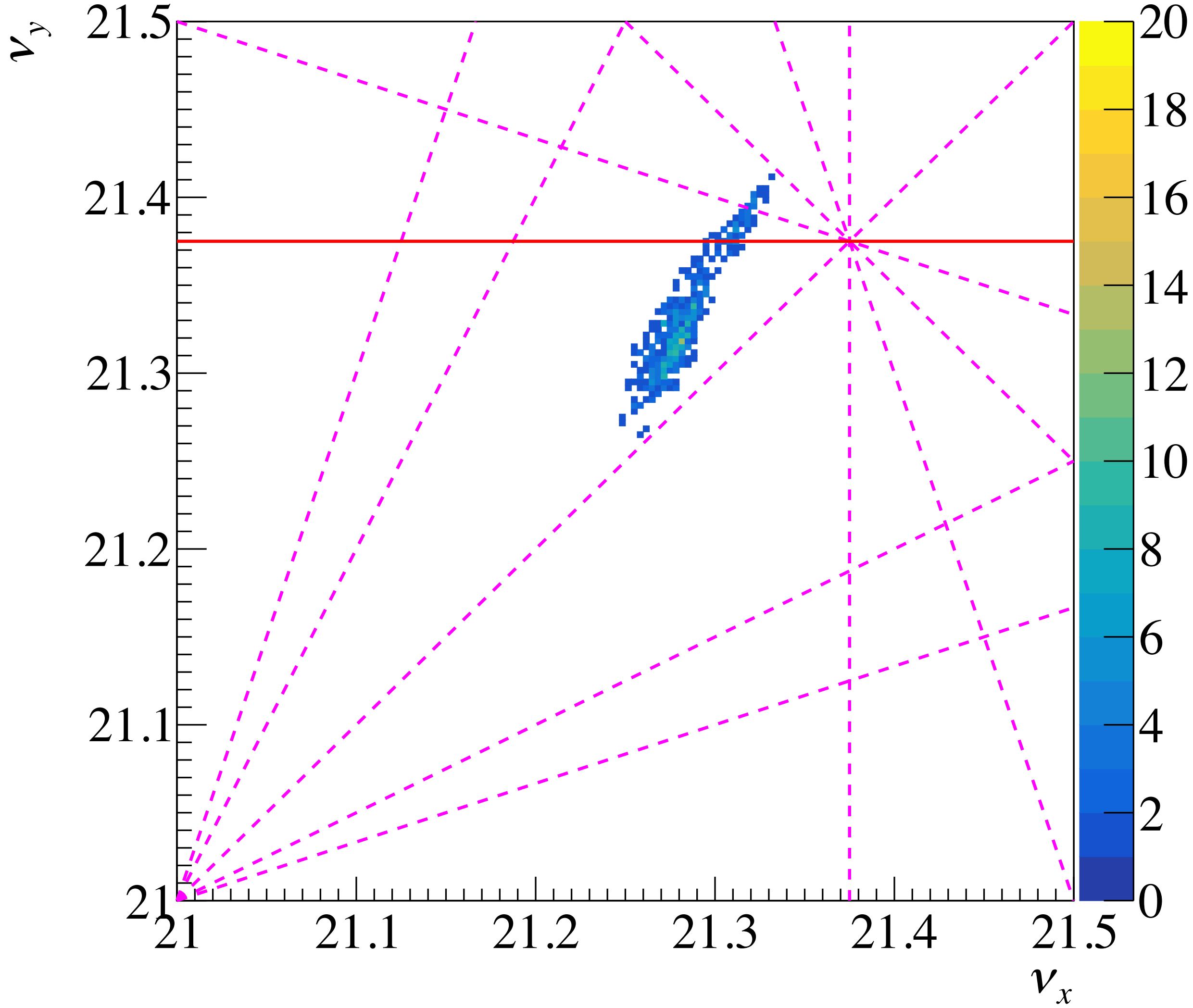



The distribution of the lost particles suggest effects of the resonance $\mathbf{8\nu_y = n}$.

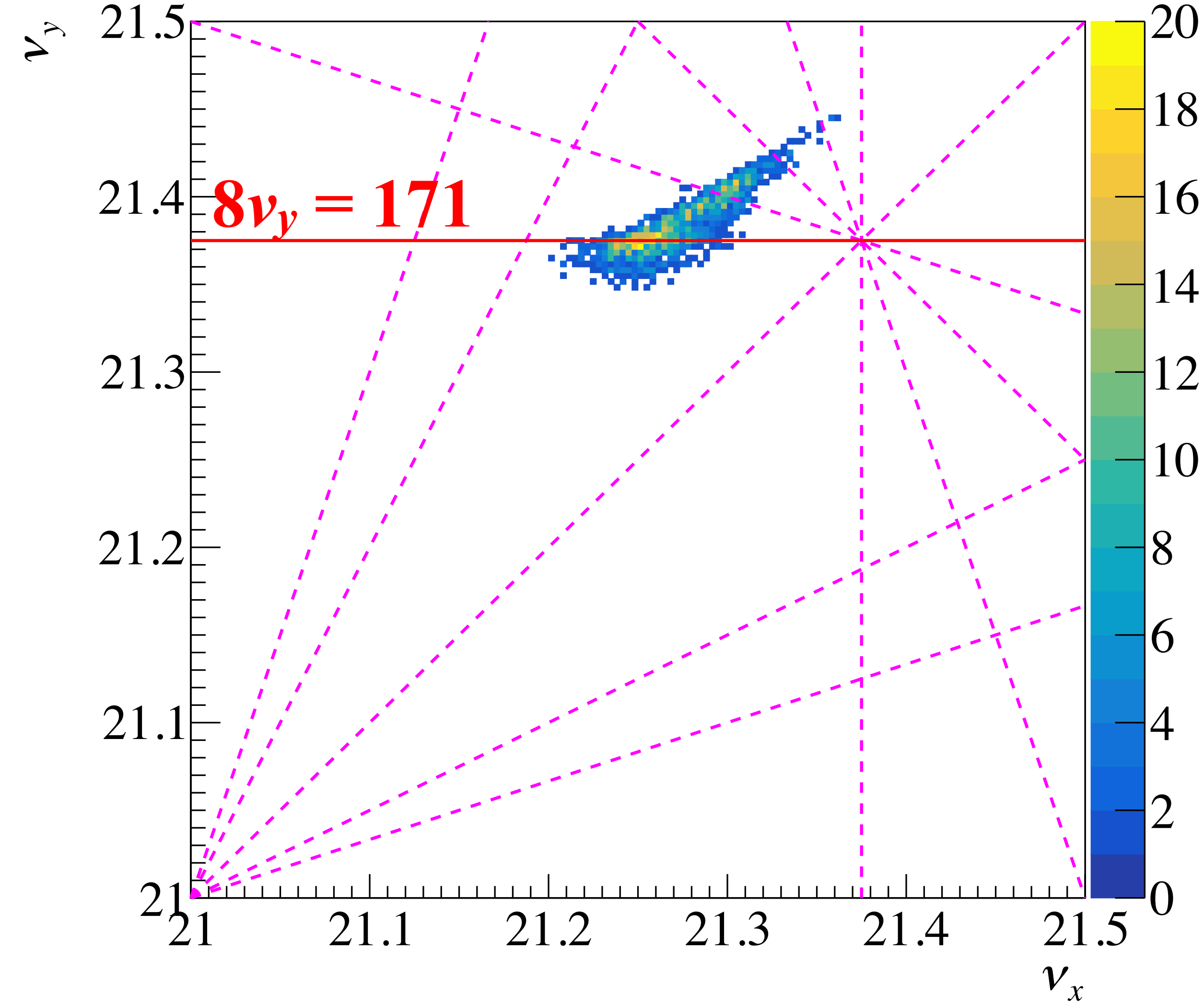
# Tunes of lost particles

Lost because $2J_x > 60\pi$ mm mrad (28.6%)




No clear relation with resonances

Lost because $2J_y > 60\pi$ mm mrad (71.4%)




Many particles are lost around the resonance $\mathbf{8\nu_y = 171}$.

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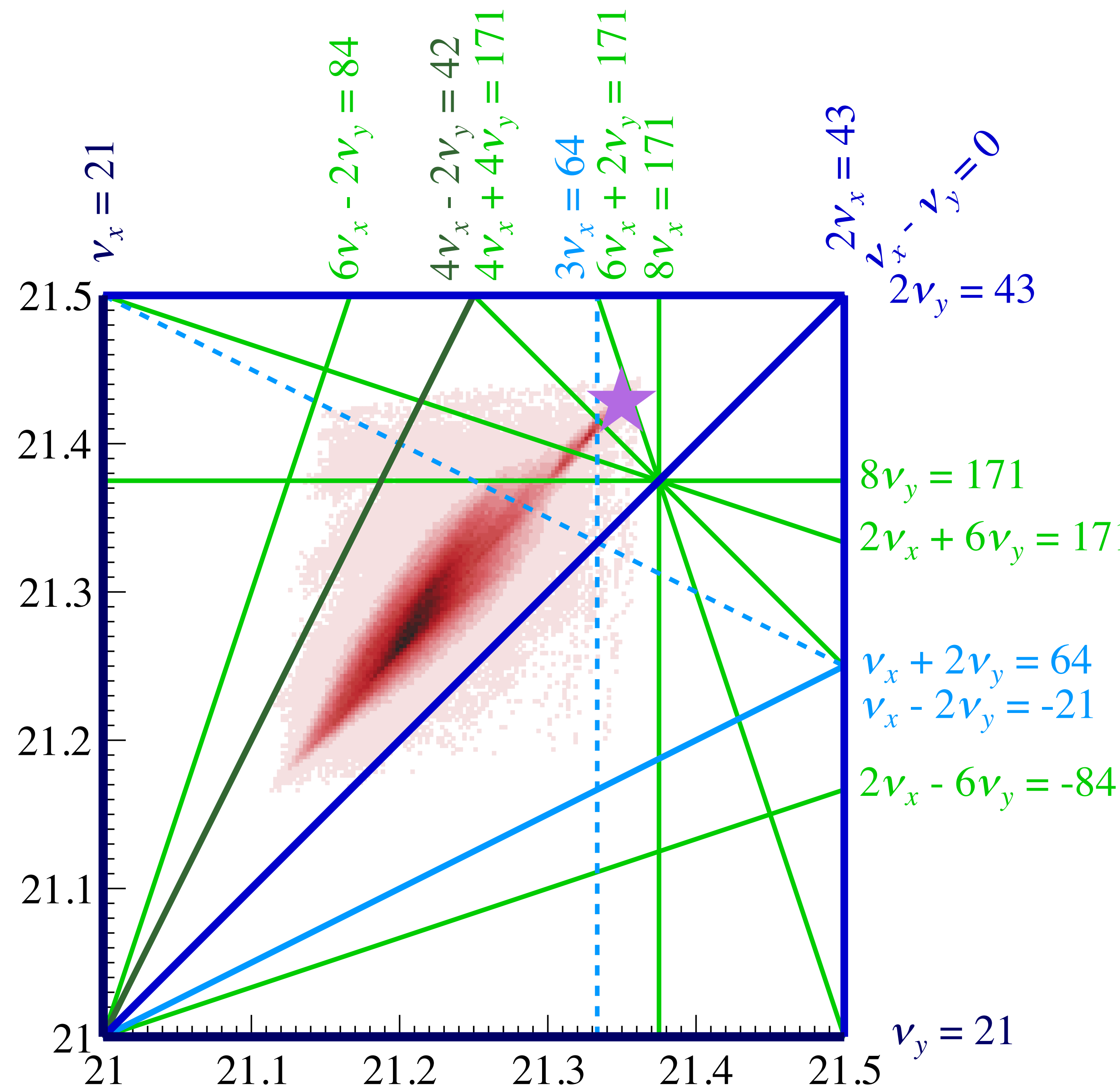
# Interpretation for $8\nu_y = 171$?

The working point is at $(\nu_x, \nu_y) = (21.35, 21.43)$.

The resonance $8\nu_y = 171$ is neither strong nor close to the working point.

Why $8\nu_y = 171$?



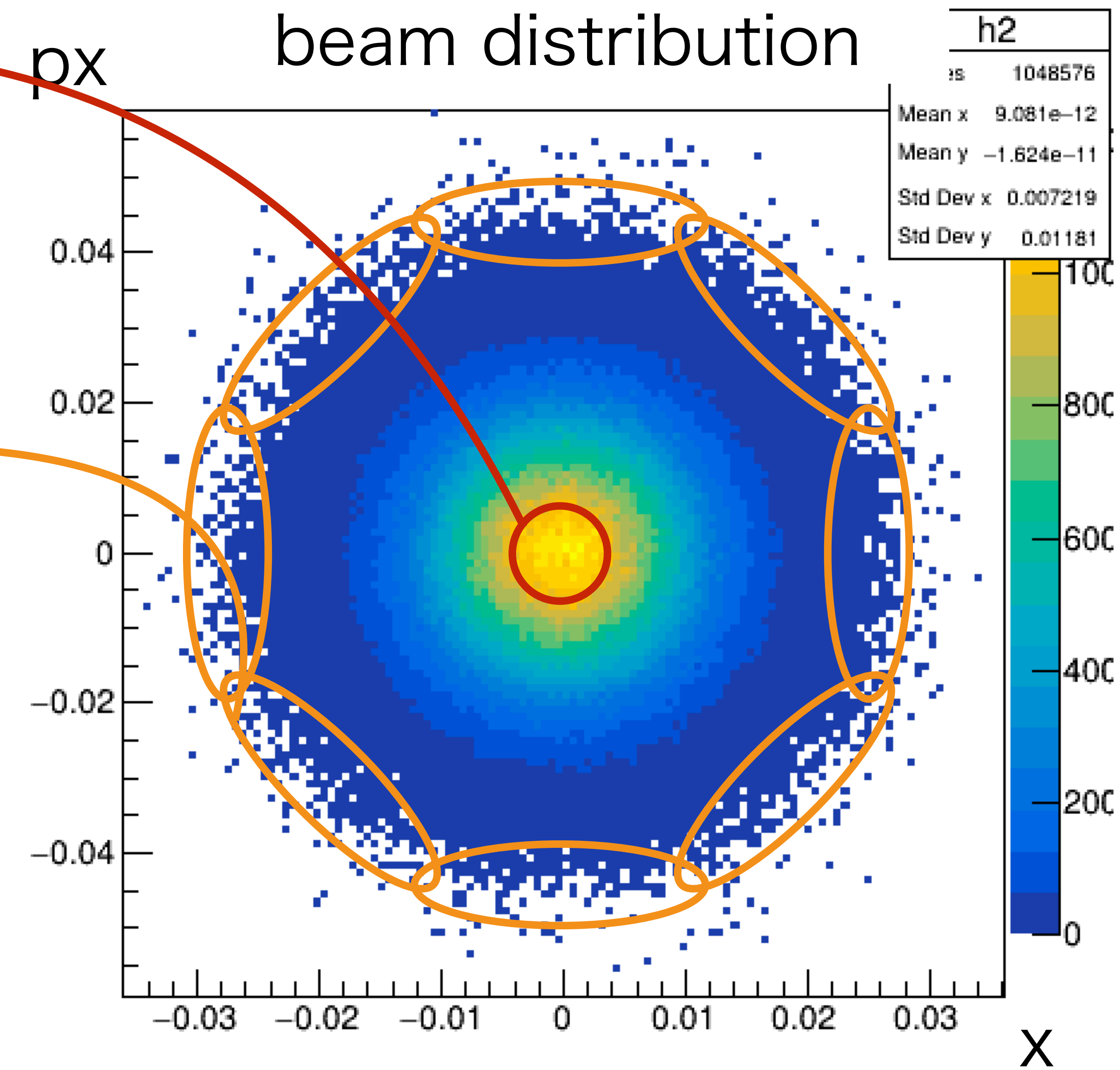
# Positions of lost particles

Particles at the center of 6D phase space.
**<u>Basically they survive.</u>**

Particles at the beam halo of 6D phase space.
**<u>These particles may be lost due to resonances.</u>**

Beam loss is caused by
**<u>the resonances which affect particles at beam halo.</u>**

Image of phase-space beam distribution



# Calculations of incoherent tunes

A particle is affected by a resonance $m_x \nu_x + m_y \nu_y = n$
when its incoherent tune satisfies $m_x \nu_{x,\text{incoh.}} + m_y \nu_{y,\text{incoh.}} = n$.

Incoherent tunes can be calculated analytically by setting the line density $\lambda$ and assuming a Gaussian distribution.

$$\nu_{\text{incoh.}} = \nu_{\text{working point}} + \underbrace{\Delta\nu_{\text{space charge}}}_{\text{space charge tune shift}} + \underbrace{\Delta\nu_{\text{sext.}}}_{\text{amplitude dependent tune shift by sextupole fields}} + \underbrace{\xi\delta}_{\text{chromaticity}}$$

$$\Delta\nu_{\text{space charge},u} = \frac{1}{2\pi}\oint \mathrm{d}\theta \frac{\partial}{\partial J_u}\frac{C}{(2\pi)^3}\iint \mathrm{d}\phi_x \mathrm{d}\phi_y U_{\text{space charge}}$$

$$U_{\text{space charge}} = \frac{\boxed{\lambda} r_0}{\gamma^3\beta^2}\int_0^\infty \mathrm{d}q \frac{\exp[-\frac{x^2}{2\sigma_x^2+q} - \frac{y^2}{2\sigma_y^2+q}]}{\sqrt{2\sigma_x^2+q}\sqrt{2\sigma_y^2+q}}$$ (2D Gaussian)

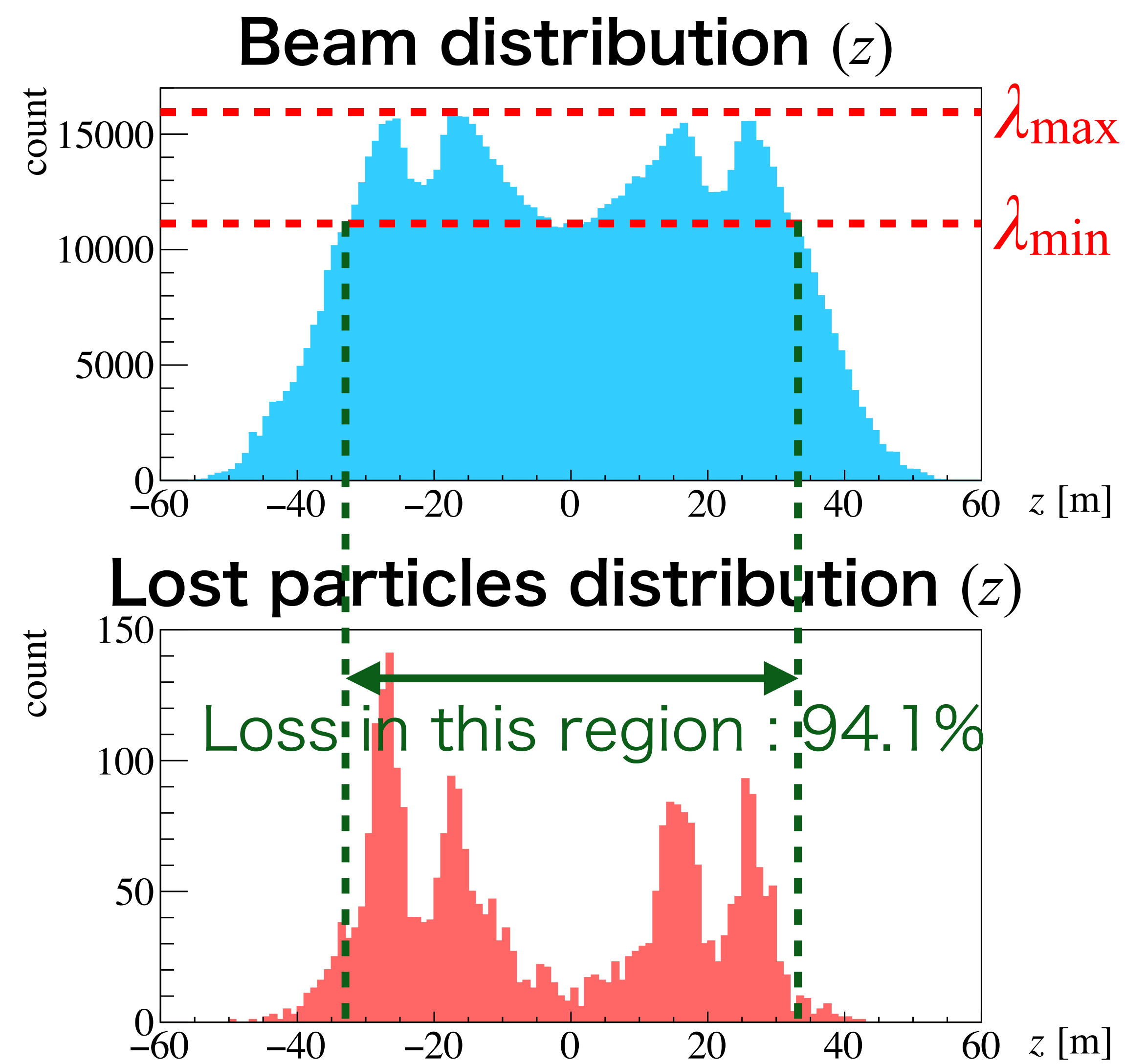
# Calculations of incoherent tunes

A particle is affected by a resonance $m_x \nu_x + m_y \nu_y = n$ when its incoherent tune satisfies $m_x \nu_{x,\mathrm{incoh.}} + m_y \nu_{y,\mathrm{incoh.}} = n$.

Incoherent tunes can be calculated analytically by setting the line density $\lambda$ and assuming a Gaussian distribution.

Calculations were performed using $\lambda_{\max}$, $\lambda_{\min}$.

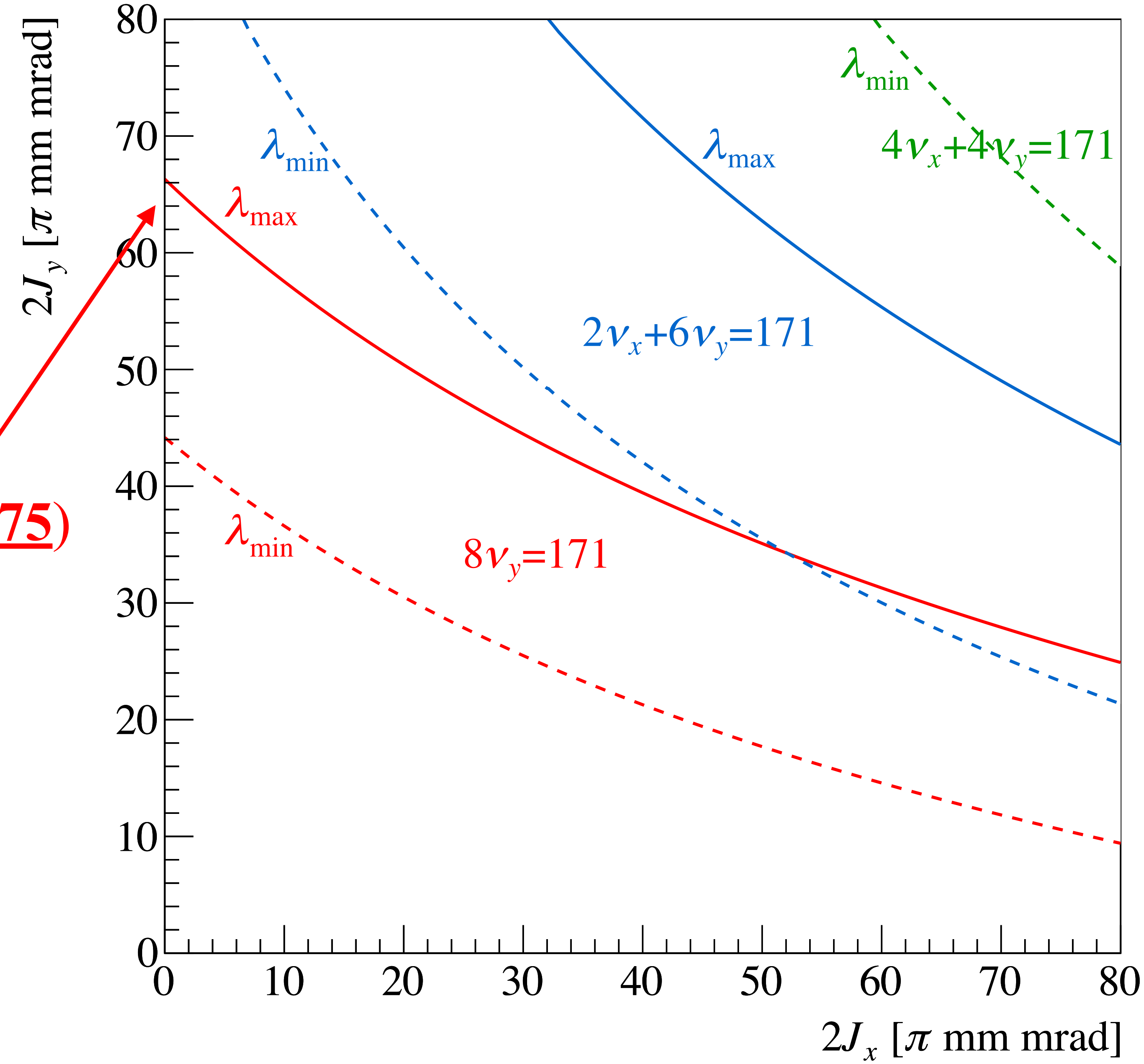
The region $\lambda_{\min} < \lambda < \lambda_{\max}$ ($|z| < 33$ m) covers 94.1% of beam losses.



# Where resonances affect

The region covered by the two solutions ($\lambda = \lambda_{\min}, \lambda_{\max}$) can be considered as where the resonance affects.

$(\nu_{\text{incoh.},x}, \underline{\boldsymbol{\nu_{\text{incoh.},y}}}) = (21.258, \underline{\mathbf{21.375}})$



# Where resonances affect

The region covered by the two solutions ($\lambda = \lambda_{\min}, \lambda_{\max}$) can be considered as where the resonance affects.

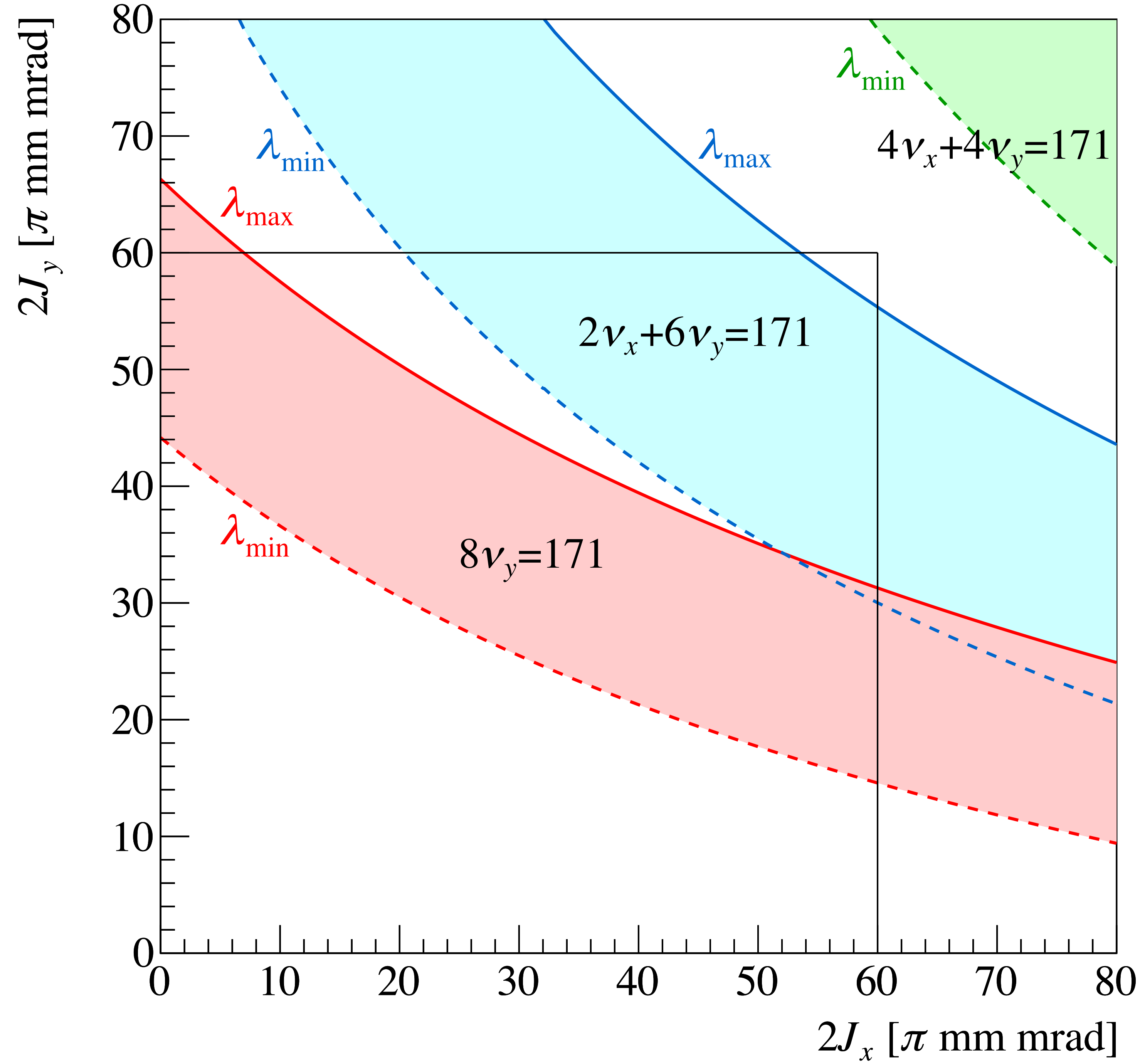
Collimator settings:

$2J_x = 2J_y = 60\pi$ mm mrad

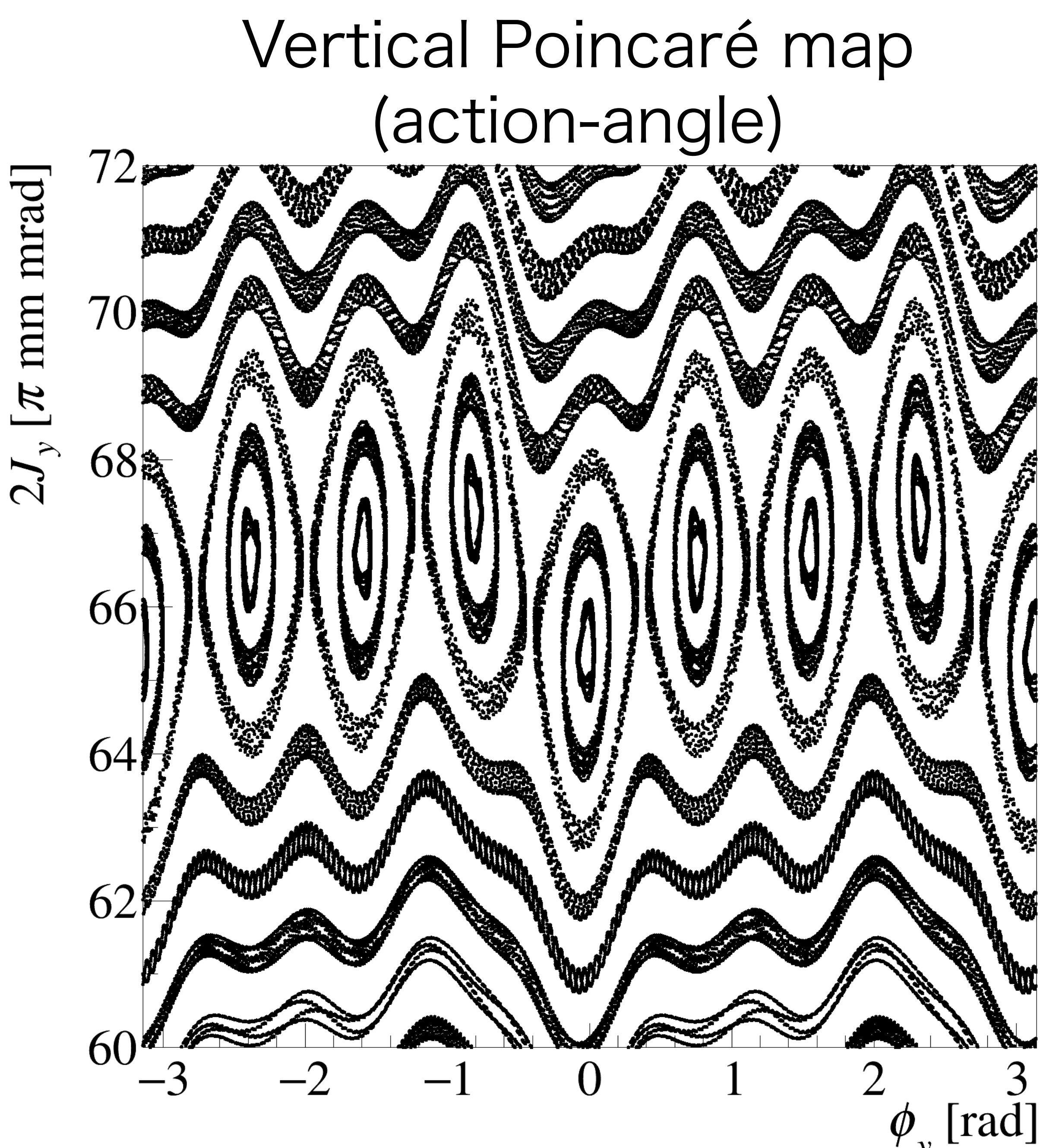
↓

“The beam halo” is also $2J_x = 2J_y = 60\pi$ mm mrad.

The resonances **$8\nu_y = 171$** and **$2\nu_y + 6\nu_y = 171$** affect $2J_x \sim 2J_y \sim 60\pi$ mm mrad.



# Vertical Poincaré map




Simulation conditions:

- Bassetti-Erskine formula (fields of Gaussian beam)
- $\lambda = \lambda_{\mathrm{max}}$
- $J_x = 0$ (initial)
- $z = \delta = 0$ (initial)

**Clear 8 resonance islands can be seen.**

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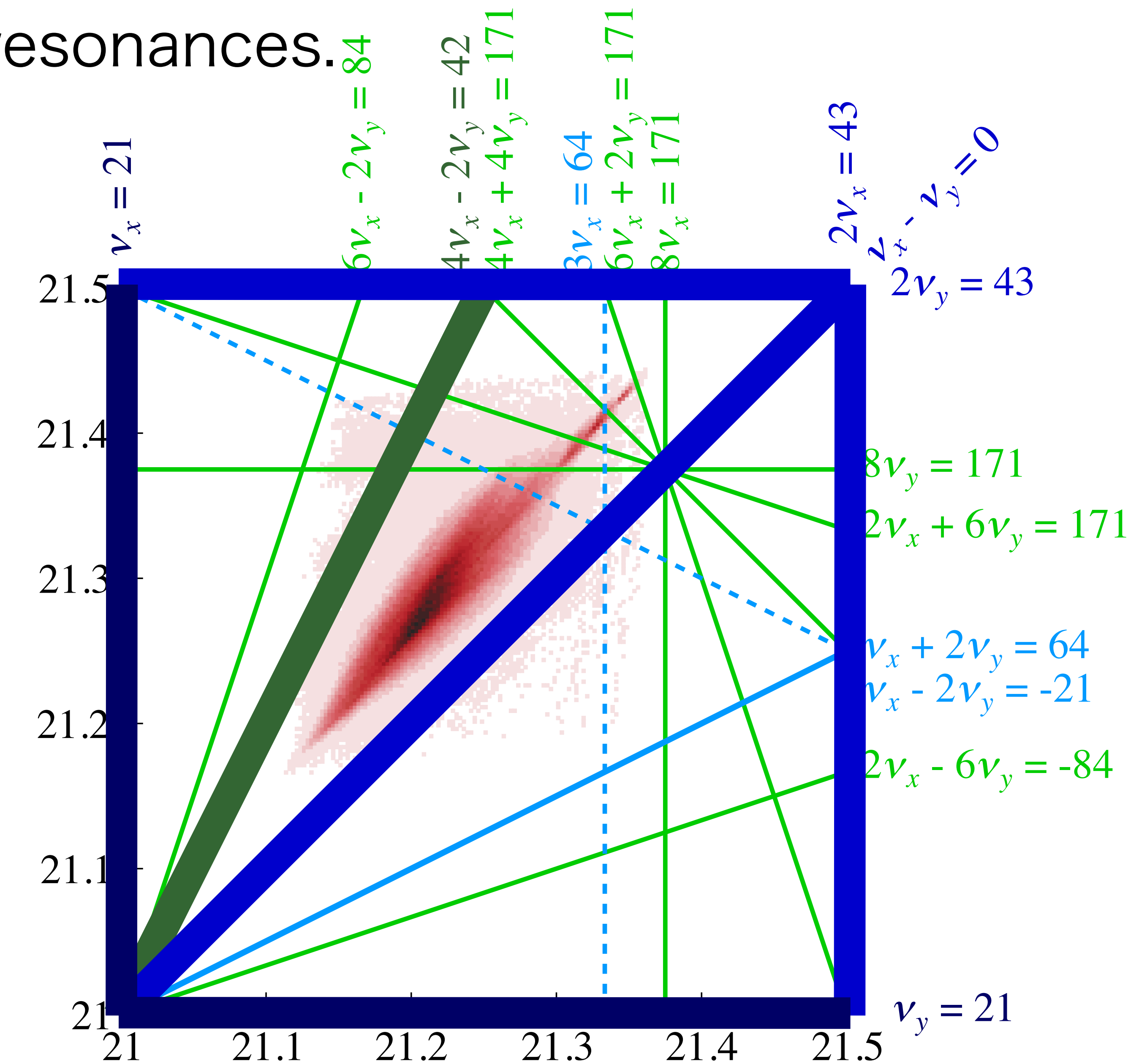
# Strategy for lower-loss operation

## Candidate 1 : Changing the working point

- We have already optimized the working point experimentally.
- Beams will hit lower-order resonances.



# Strategy for lower-loss operation

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## Candidate 2 : Corrector magnets

- Need 16-pole magnets
- Costly, difficult?

# Strategy for lower-loss operation

## Candidate 1 : Changing the working point

- We have already optimized the working point experimentally.
- Beams will hit lower-order resonances.

## Candidate 2 : Corrector magnets

- Need 16-pole magnets
- Costly, difficult?

## Candidate 3 : A new optics maintaining the working point

- The “Resonance Driving Term” can be changed by rebalancing the phase advances maintaining the working point

# Resonance potential

Let us define the resonance potential $U_{mx,my,n}$ as

$$U_{\text{space charge}} = \sum_{m_x,m_y,n} U_{m_x,m_y,n} \cos(m_x\phi_x + m_y\phi_y - n\theta + \xi_{m_x,m_y,n}).$$

It can be derived as

$$U_{m_x,m_y,n} e^{i\xi_{m_x,m_y,n}} = 2\frac{1}{(2\pi)^3} \oint \mathrm{d}\theta \iint \mathrm{d}\phi_x \mathrm{d}\phi_y U_{\text{space charge}} e^{-i[m_x\phi_x + m_y\phi_y - n\theta]}.$$

Assuming a Gaussian distribution, the potential of $8\nu_y = 171$ is

$$U_{0,8,171} e^{i\xi_{0,8,171}} = \frac{\lambda r_0}{\pi\gamma^3\beta^2} \oint \mathrm{d}s e^{i[8\chi_y - \underbrace{(8\nu_y - 171)}_{\text{fixed}}\theta]} \int_0^\infty \mathrm{d}q \frac{e^{-\frac{J_x\beta_x}{2\sigma_x^2+q} - \frac{J_y\beta_y}{2\sigma_y^2+q}} I_0(\frac{J_x\beta_x}{2\sigma_x^2+q}) I_4(\frac{J_y\beta_y}{2\sigma_y^2+q})}{\sqrt{2\sigma_x^2 + q}\sqrt{2\sigma_y^2 + q}}.$$

phase advance

$$\chi_y(s) = \int_0^s \frac{\mathrm{d}s}{\beta_y} \quad \cdots \text{ changeable}$$

$$\chi_y(C) = 2\pi\nu_y \quad \cdots \text{ fixed}$$

$U_{0,8,171}$ is changeable maintaining the working point.

# How to change $U_{0,8,171}$

Even with the restriction of the working point,
there are a lot of solutions for the beam optics.

## Other restrictions/suggestions

- Keep achromat lattice ($\Delta\Psi_{\mathrm{arc},\,x} = 6 \times 2\pi$)
- Better to change globally than locally.

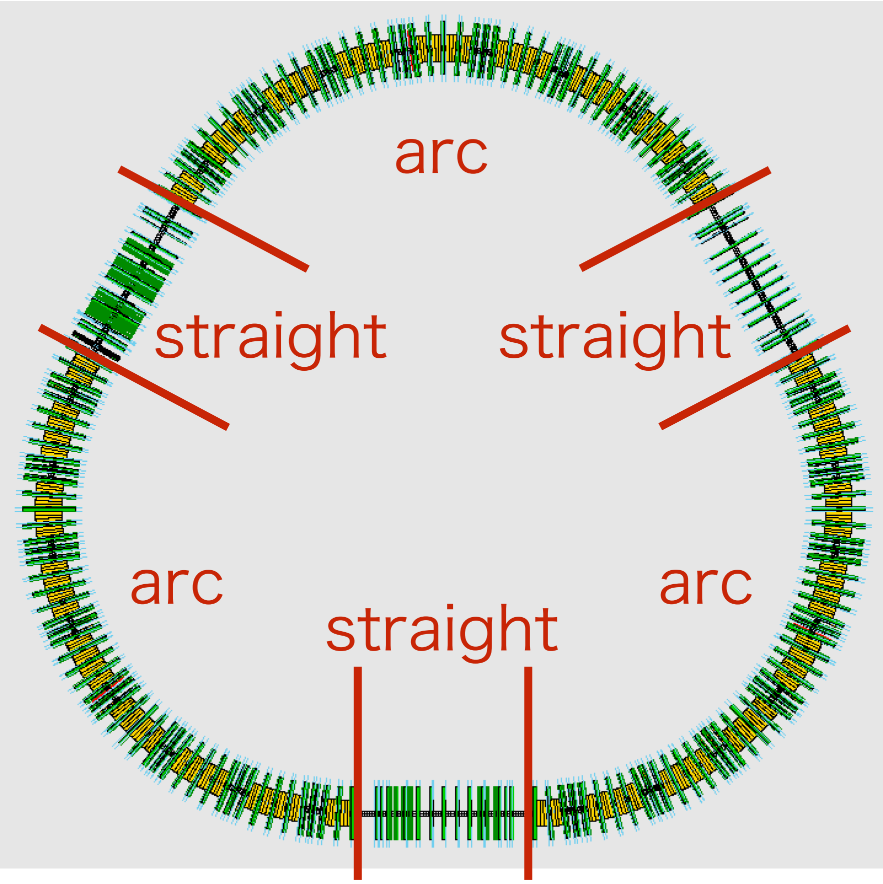
$$\downarrow$$

We chose $\Delta\Psi_{\mathrm{arc},\,y}$ as a scanning knob.

$$\Delta\Psi_{\mathrm{straight},\,y} = (2\pi\nu_y - 3\Delta\Psi_{\mathrm{arc},\,y})/3$$

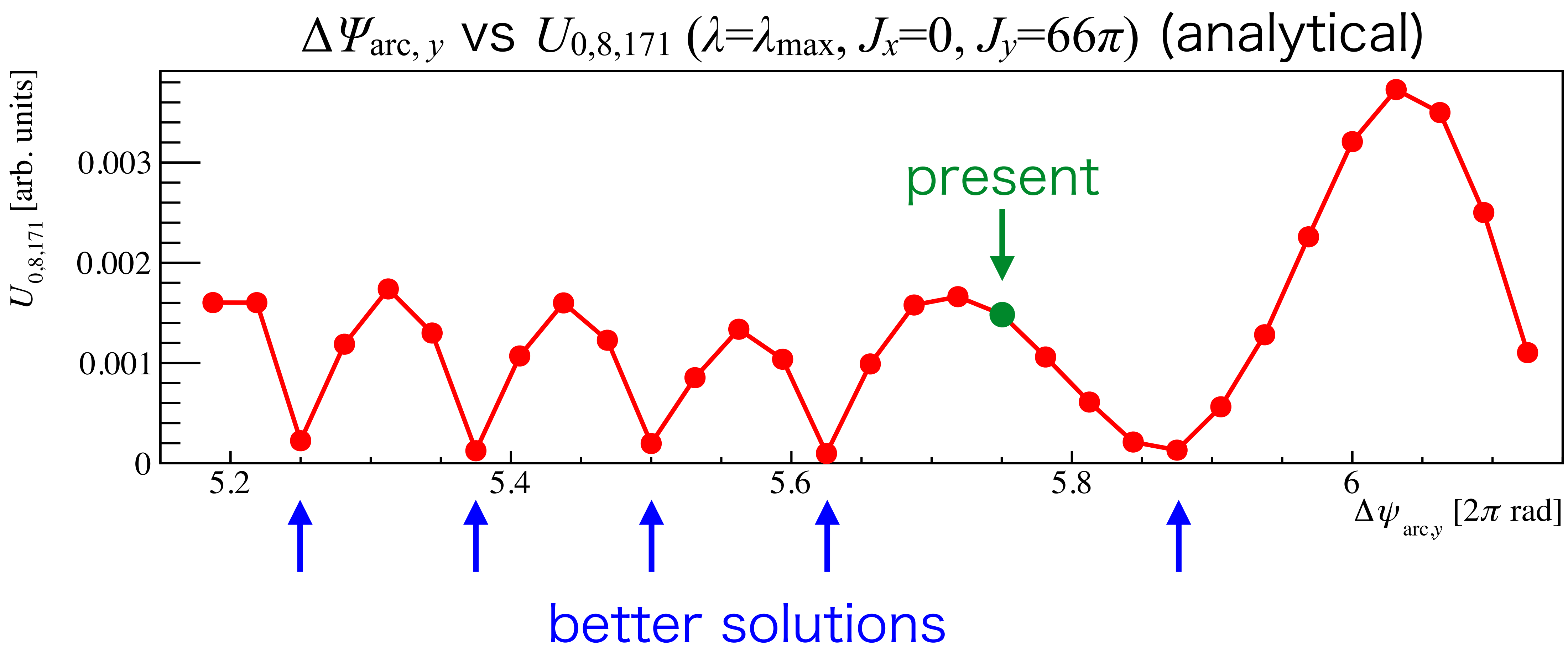
$$\Delta\Psi_{\mathrm{arc},\,x} = 6 \times 2\pi \quad \text{(fixed)}$$

$$\Delta\Psi_{\mathrm{straight},\,x} = (2\pi\nu_x - 3\Delta\Psi_{\mathrm{arc},\,x})/3 \quad \text{(fixed)}$$

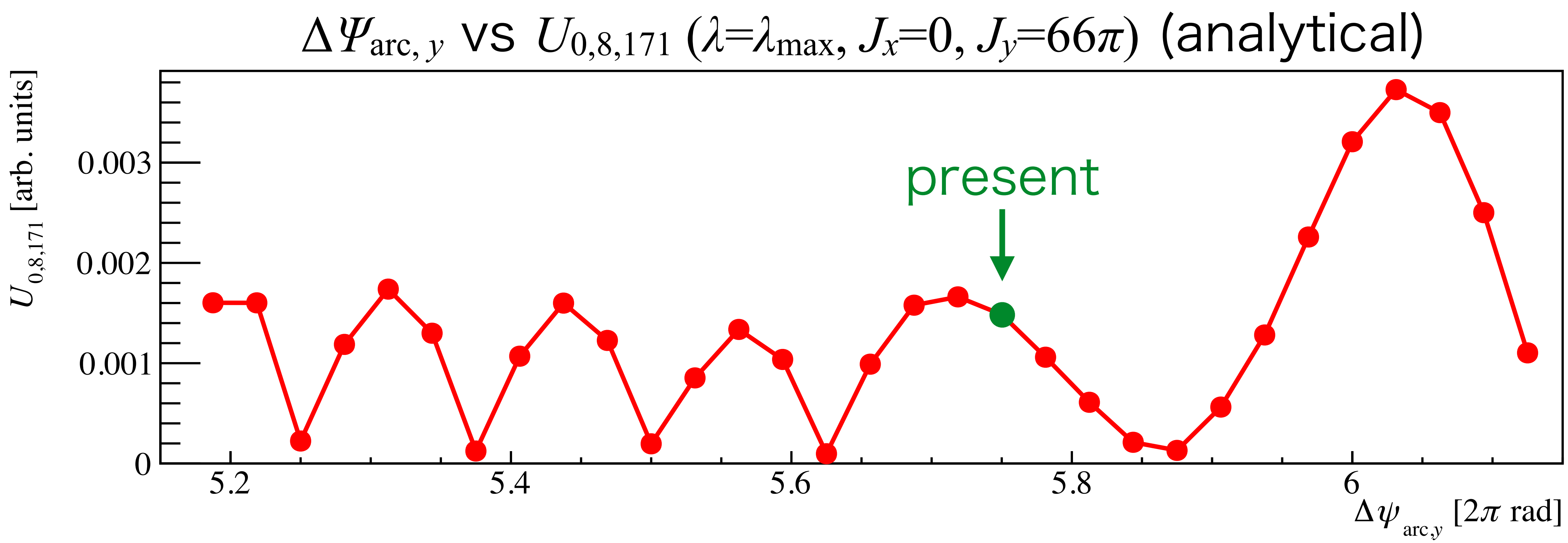


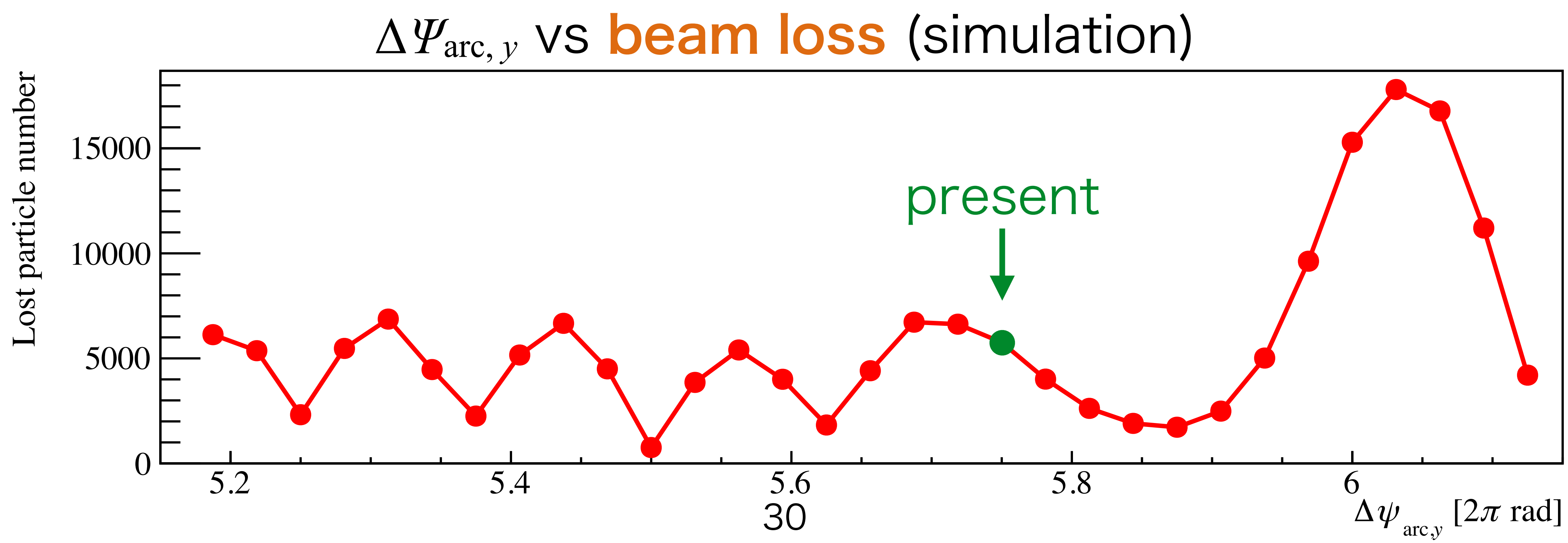

$$3\Delta\Psi_{\mathrm{straight}} + 3\Delta\Psi_{\mathrm{arc}} = 2\pi\nu$$

# $\Delta\Psi_{\mathrm{arc},\,y}$ scan



# $\Delta\Psi_{\mathrm{arc},\,y}$ scan

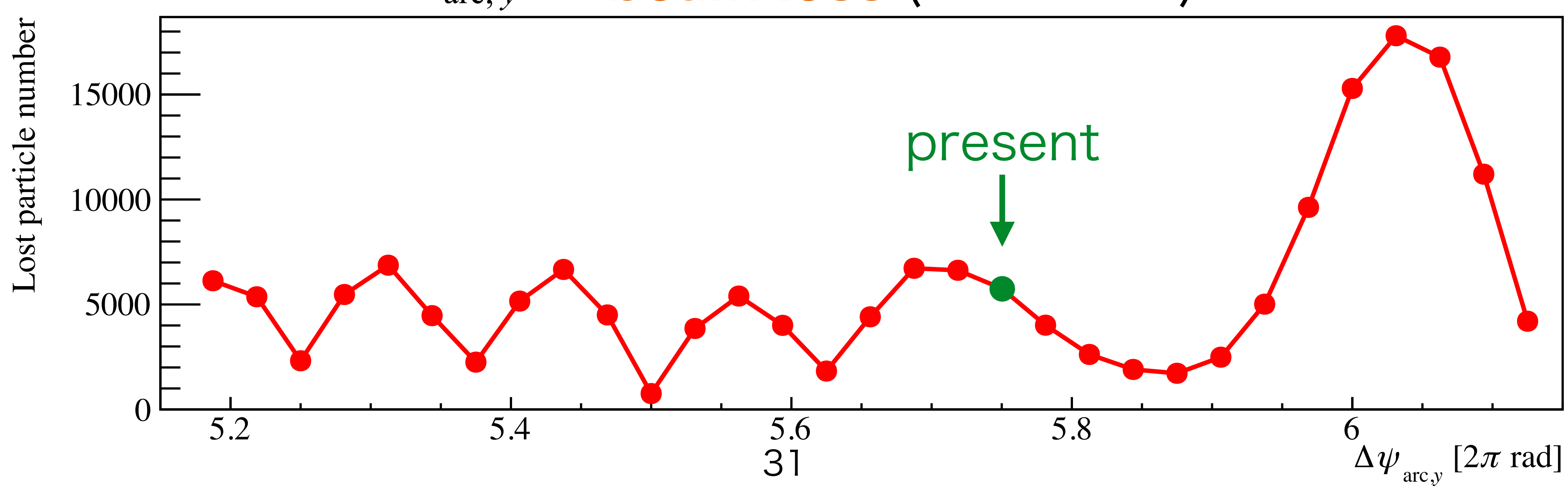


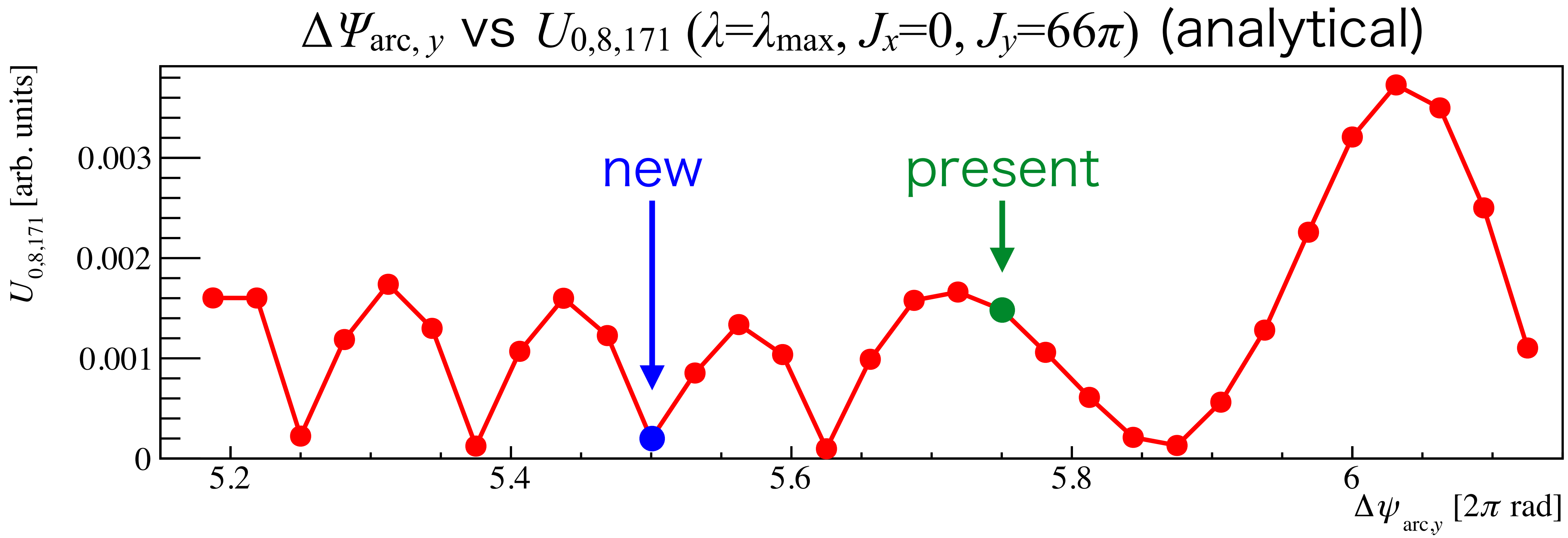
# $\Delta\Psi_{\mathrm{arc},\,y}$ scan

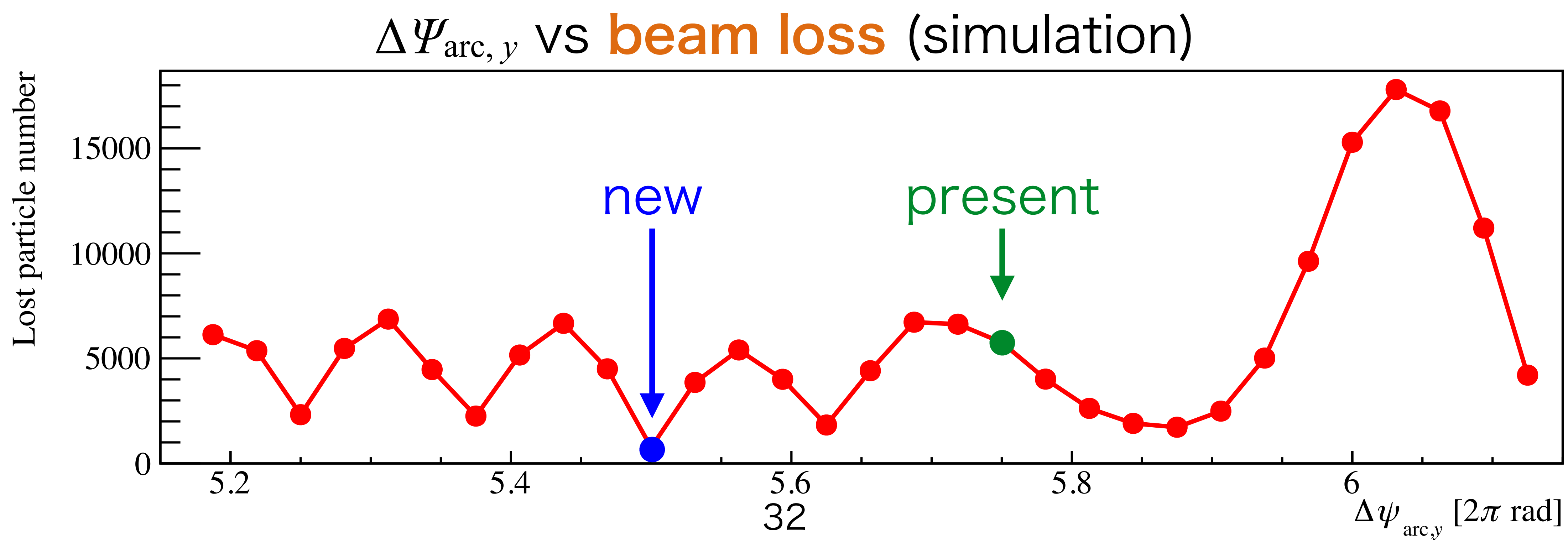
**very similar!**
**Beam loss is caused by $8\nu_y = 171$.**


$\Delta\Psi_{\mathrm{arc},\,y}$ vs **beam loss** (simulation)

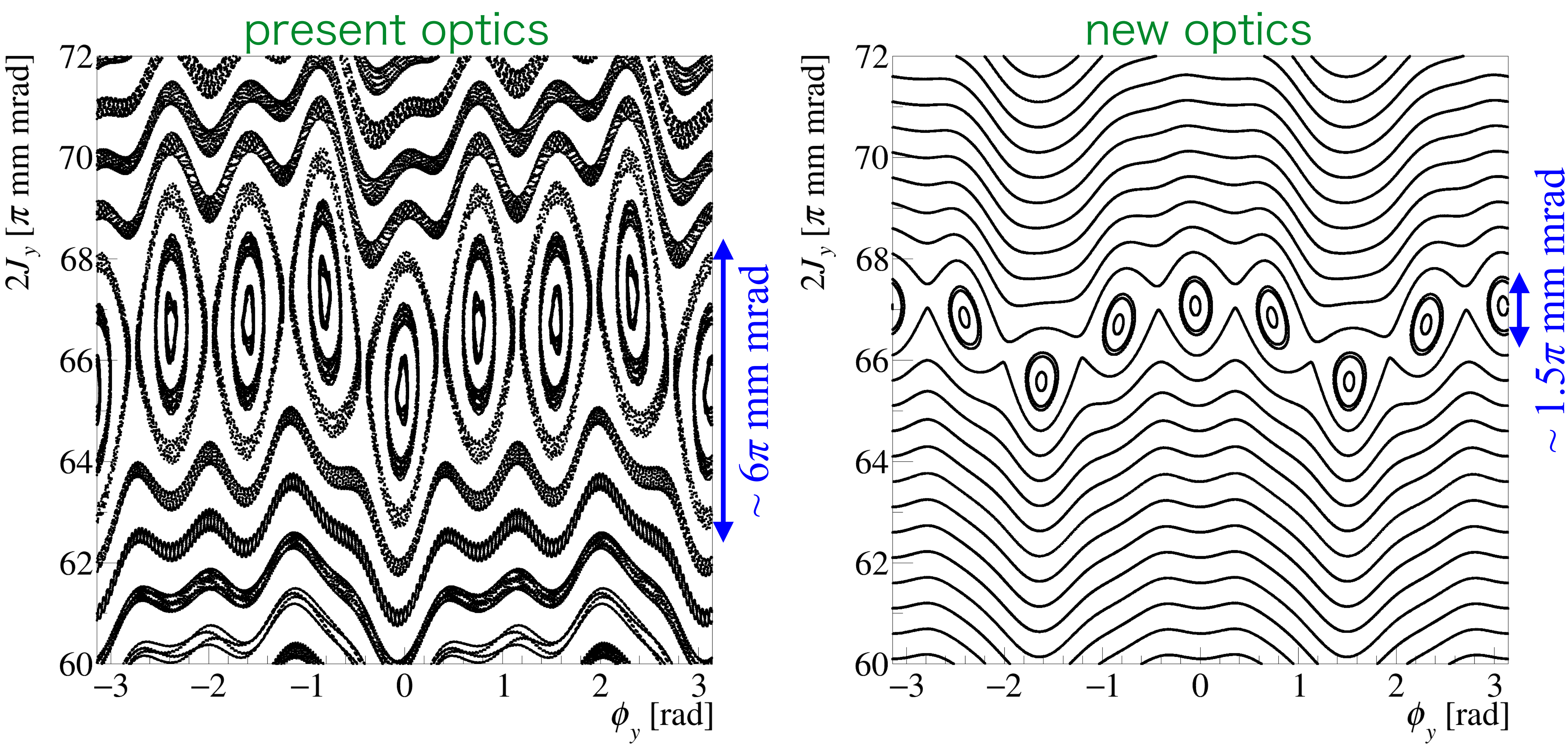


# $\Delta\Psi_{\mathrm{arc},\,y}$ scan



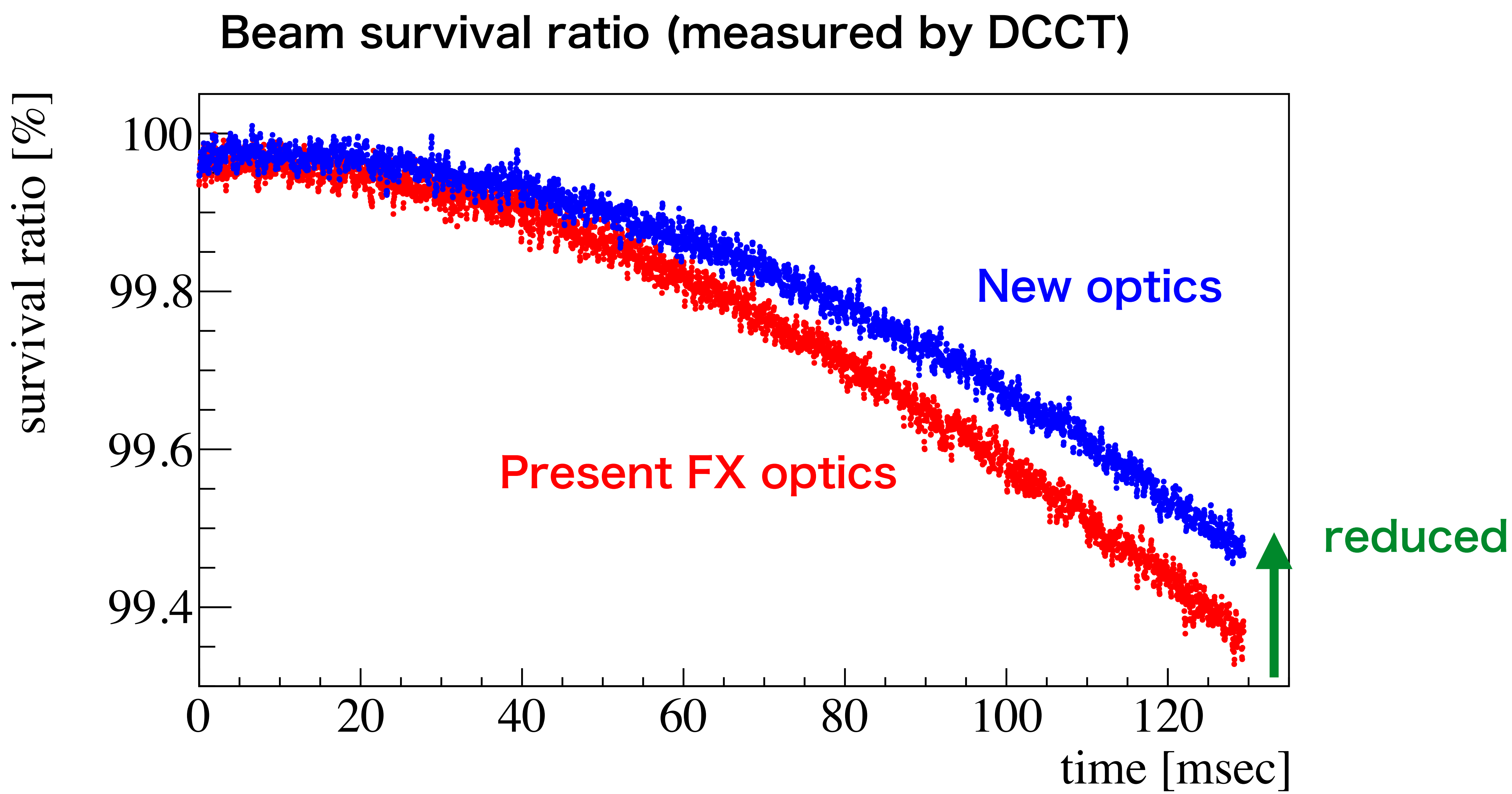
# Vertical Poincaré map




**The resonance $8\nu_y = 171$ is weakened!**

# Beam loss measurement

We measured beam losses with the present and new optics.

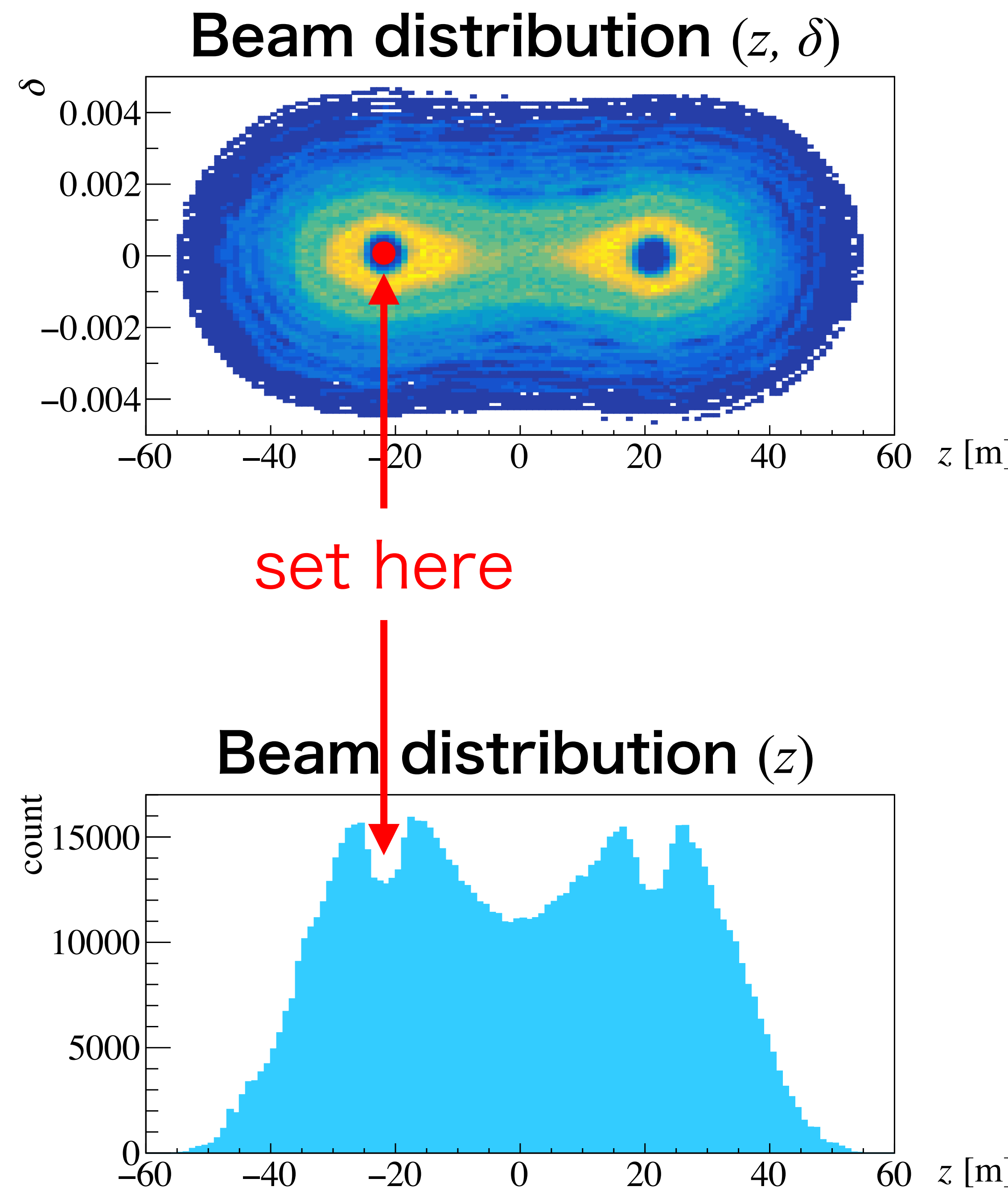


# Frequency map analysis

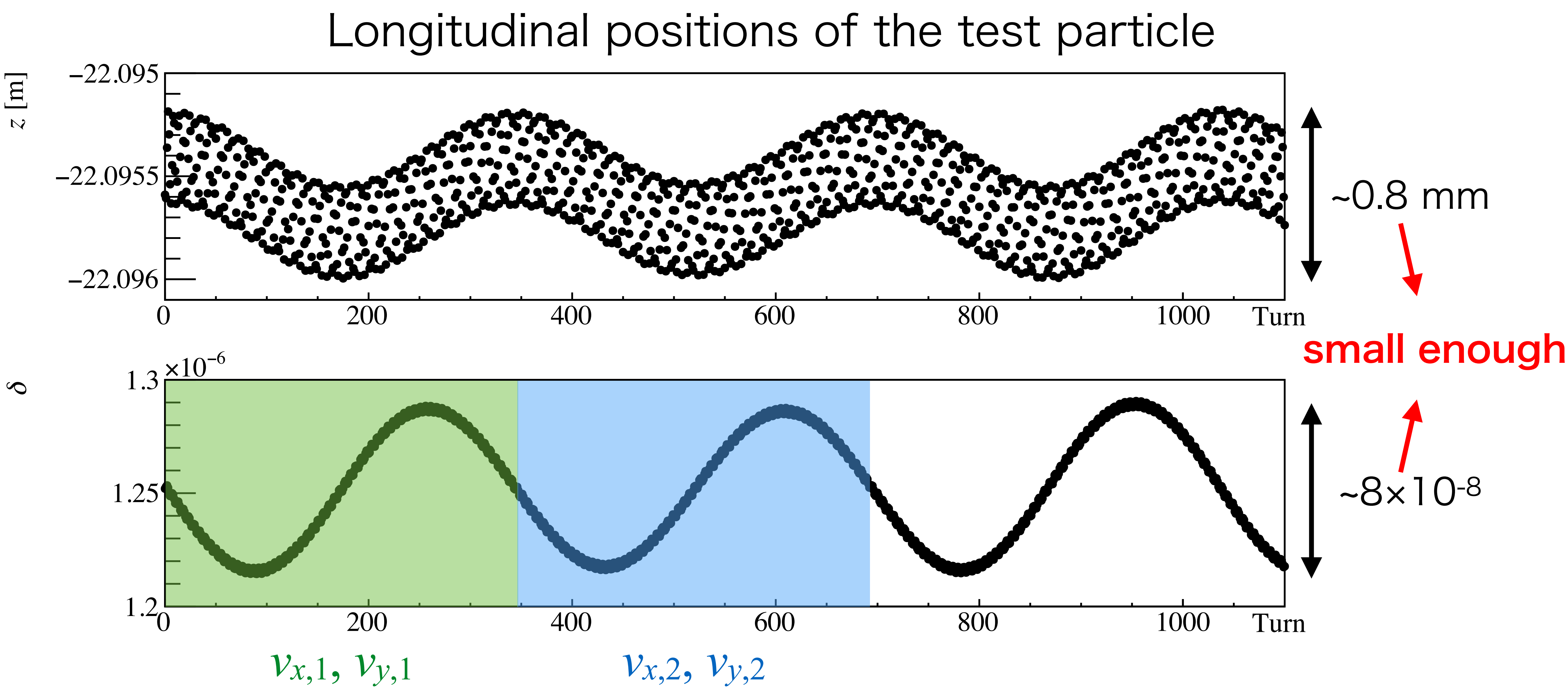
Frequency map analysis (FMA) was performed with both optics to visualize resonances.

The space charge potentials were constructed by PIC simulation and then fixed ("frozen model").

Initial longitudinal positions of the test particles were set as $(z, \delta) = (-22\ \mathrm{m}, 0)$ to keep $\delta = 0$.

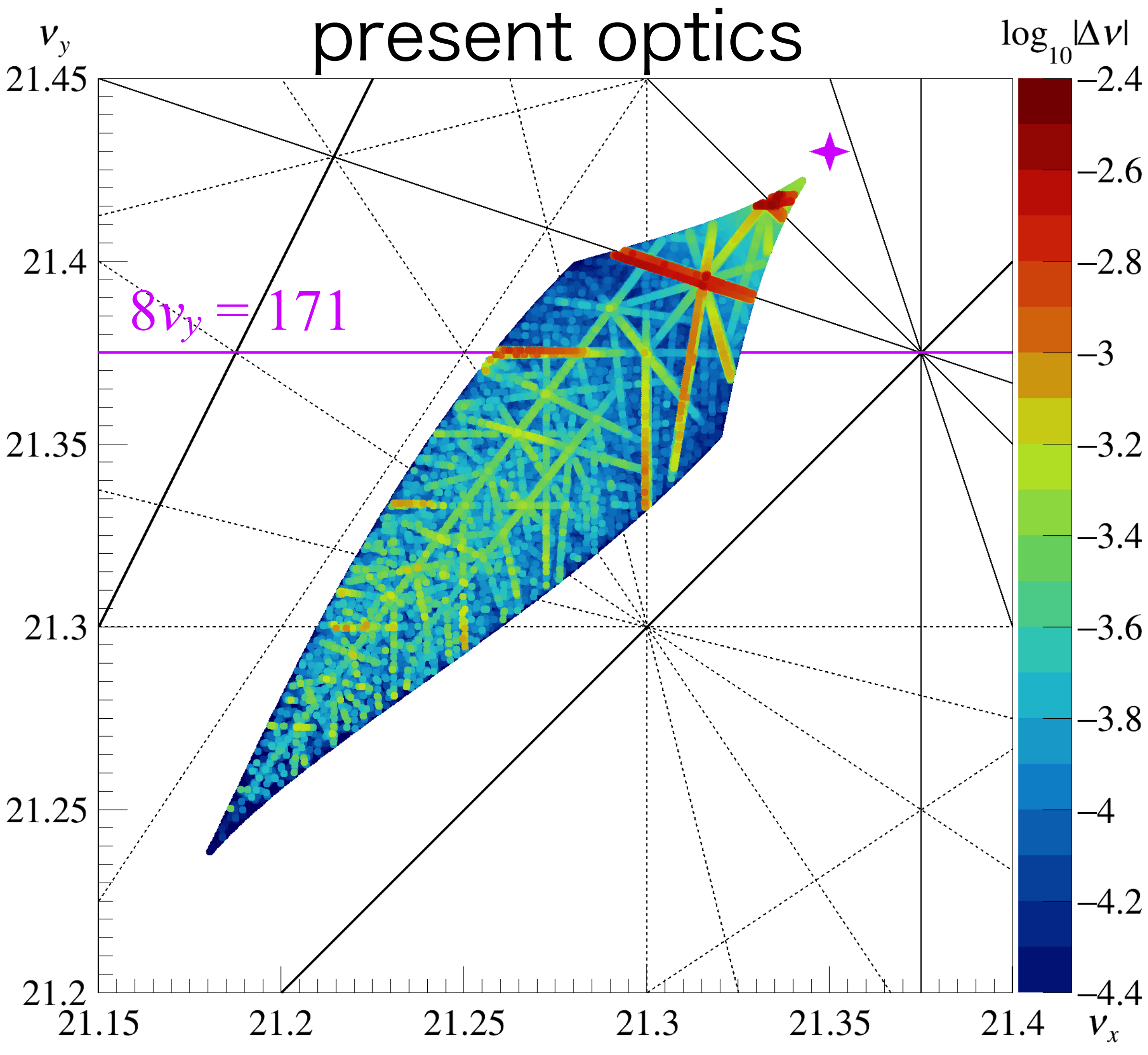


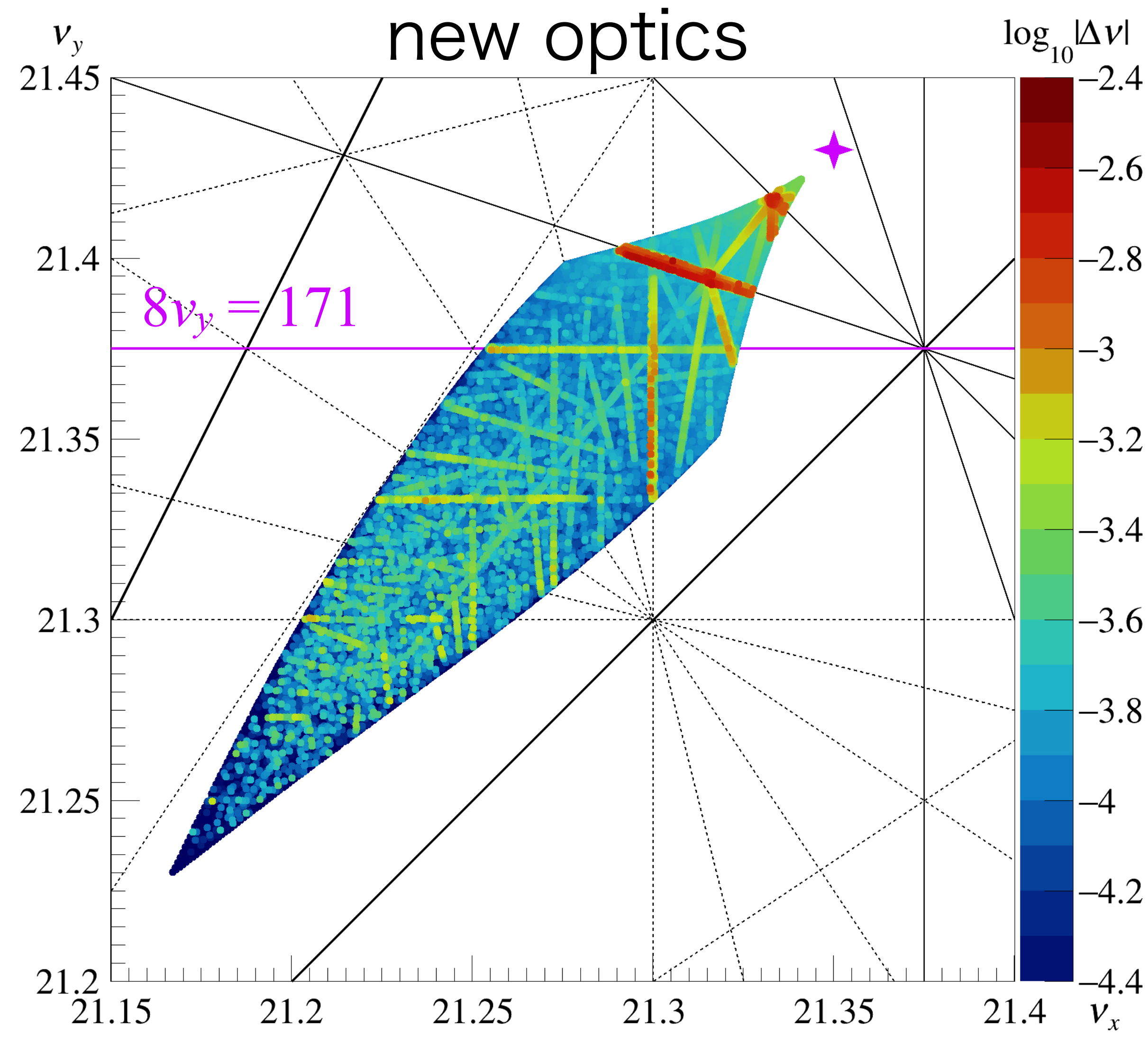
# FMA longitudinal motions




Indicator : $\log_{10}|\Delta\nu| = \log_{10}\sqrt{(\nu_{x,2}-\nu_{x,1})^2+(\nu_{y,2}-\nu_{y,1})^2}$

# FMA results




Suppression of the resonance $8\nu_y = 171$ was also confirmed via FMA.

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# Summary

Space charge induced structure resonance $8\nu_y$=171 causes beam loss in the J-PARC MR,
because it affects particles at beam halo.

A new beam optics was developed to suppress the resonance $8\nu_y$=171 and reduce beam loss.

Superiority of the new optics was confirmed via

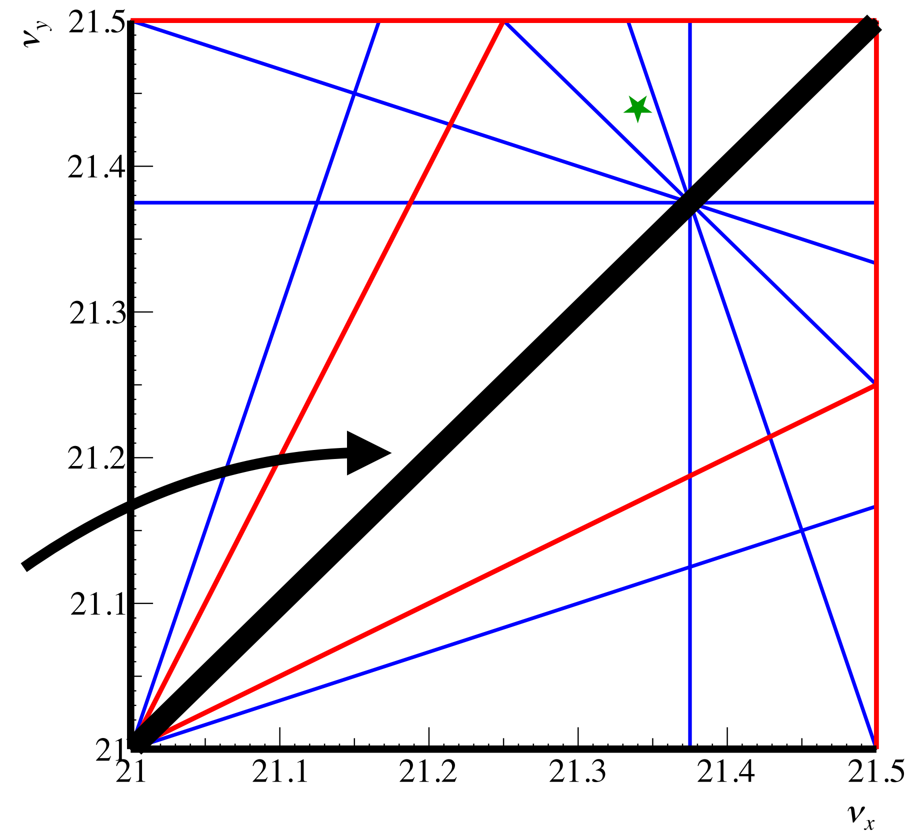
- resonance potentials (analytical calculation),
- beam loss simulations,
- Poincaré maps,
- beam loss measurements,
- frequency map analysis.

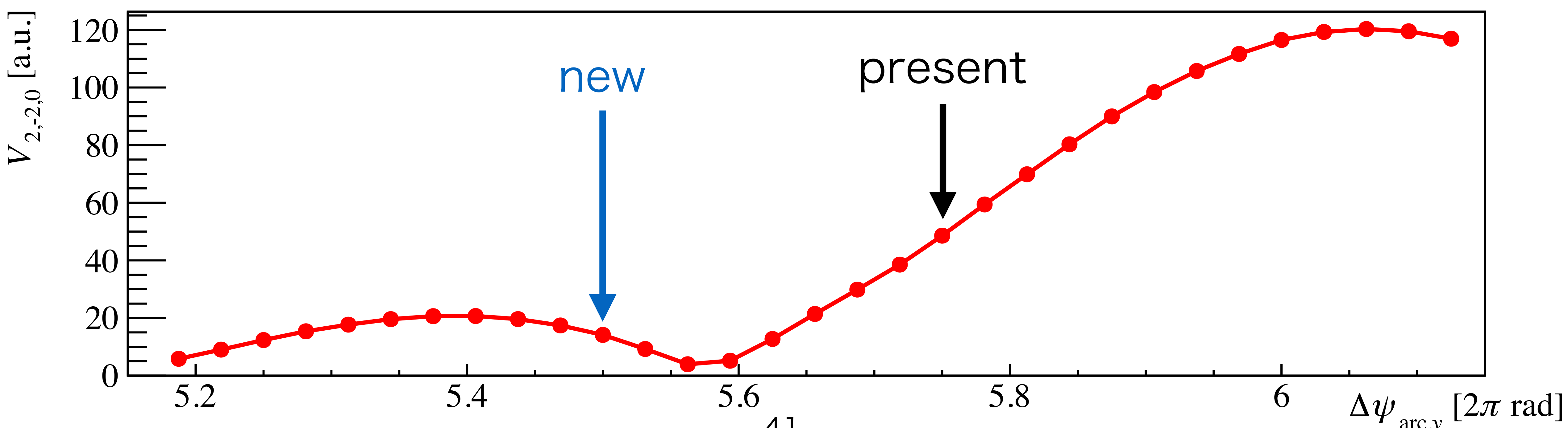
# Backup

# Strength of other resonances

In addition to $8\nu_y = 171$,
the 4th order structure resonance
$2\nu_x - 2\nu_y = 0$ can be weaken by applying
the new optics.

$2\nu_x - 2\nu_y = 0$



# Resonance potential vs RDT

## Resonance potential

- Fourier transform of a potential → accurate
- depends on $J_x$, $J_y$

$$U_{\text{space charge}} = \sum_{m_x, m_y, n} U_{m_x, m_y, n} \cos(m_x \phi_x + m_y \phi_y - n\theta + \xi_{m_x, m_y, n})$$

$$U_{0,8,171} e^{i\xi_{0,8,171}} = 2\frac{1}{(2\pi)^3} \oint \mathrm{d}\theta \iint \mathrm{d}\phi_x \mathrm{d}\phi_y U_{\text{space charge}} e^{-i[8\phi_y - 171\theta]}$$

## Resonance Driving Term

- Assume potential $x^{mx}y^{my}$ → One aspect of resonance potential
- independent of $J_x$, $J_y$

$$U_{0,8,171} = G_{0,8,171} J_y^4 + A_{0,5} J_y^5 + A_{0,6} J_y^6 + \cdots + A_{1,4} J_x J_y^4 + \cdots$$

$$G_{0,8,171} = \frac{1}{4!} \frac{\partial^4 U_{0,8,171}(J_x, J_y)}{\partial J_y^4}\bigg|_{J_x = J_y = 0}$$