



Space charge induced resonances and suppression in J-PARC MR

Takaaki Yasui (KEK/J-PARC)

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

Outline

1. Introduction

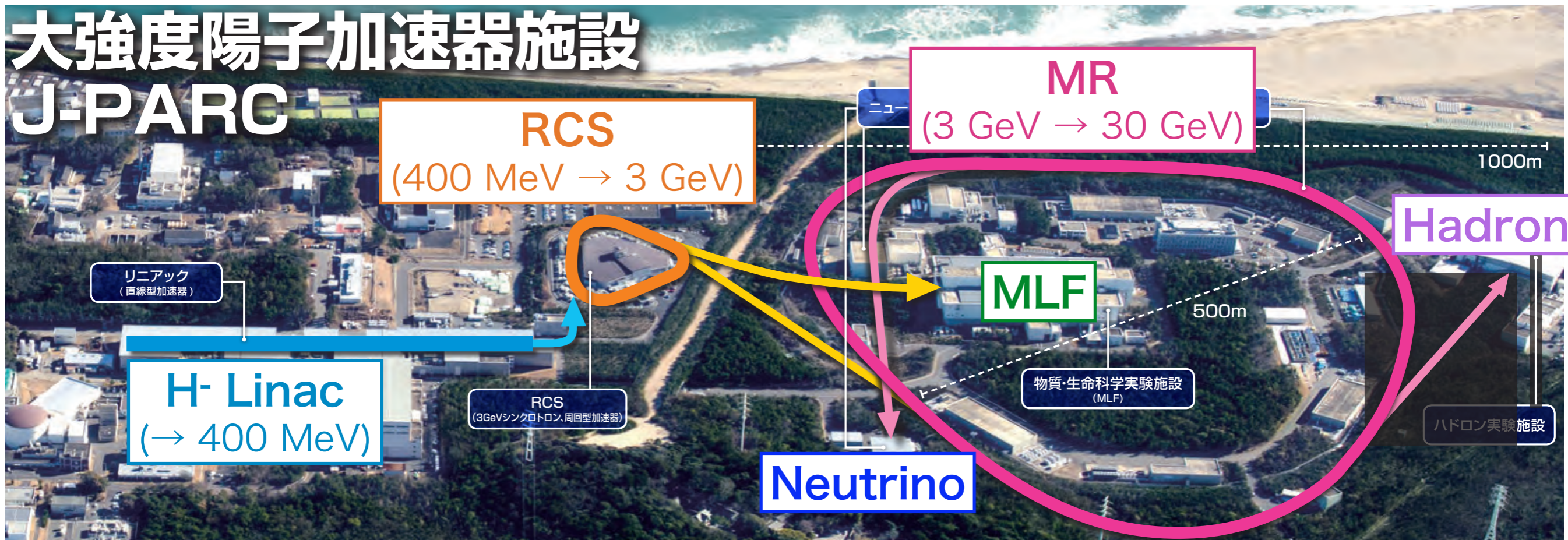
2. Identification of source of beam loss

3. Mechanism of beam loss

4. A new optics for reducing beam loss

5. Summary

J-PARC MR



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

Upgrade plan: 1.3 MW FX (fast extraction) operation

FX beam power upgrade plan

$$\text{Power} = \text{Energy}(30 \text{ GeV}) \times \text{Number of protons} / \text{Cycle time}$$

JFY2021	515 kW	2.66×10^{14} ppp	2.48 s
	Long-term shutdown for faster cycling		
Present	760 kW	2.17×10^{14} ppp	1.36 s
Future	1300 kW	3.3×10^{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

- $\Delta x = \eta_x \frac{\Delta B}{B}$, $|\Delta K_1| = |K_2 \Delta x|$ 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

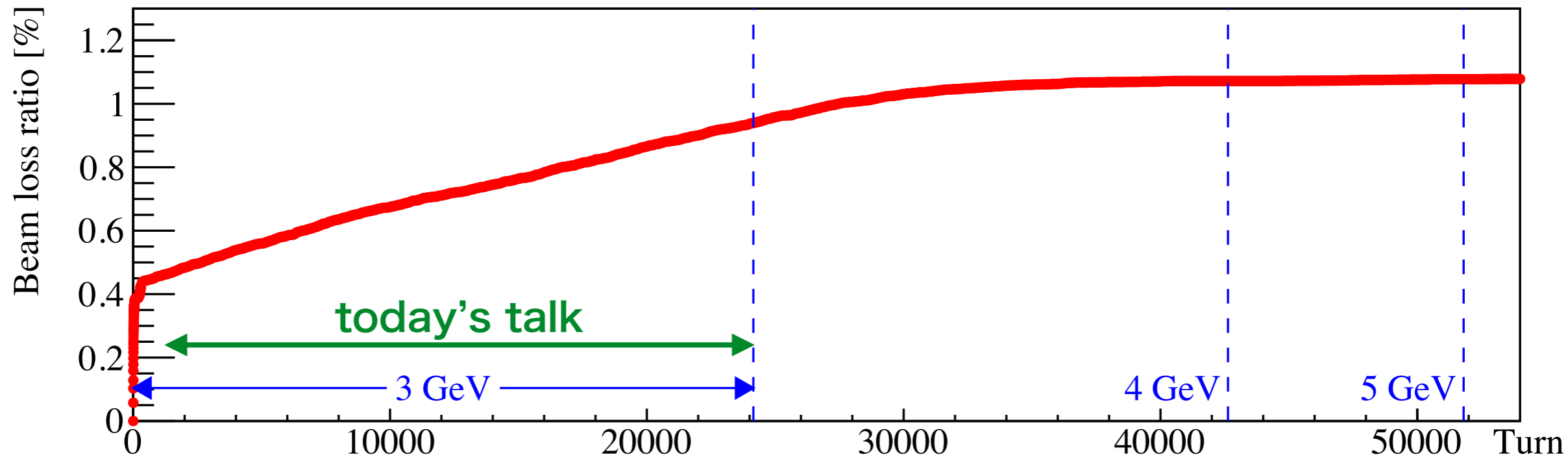
3. Structure resonances induced by space charge effects

- Today's talk

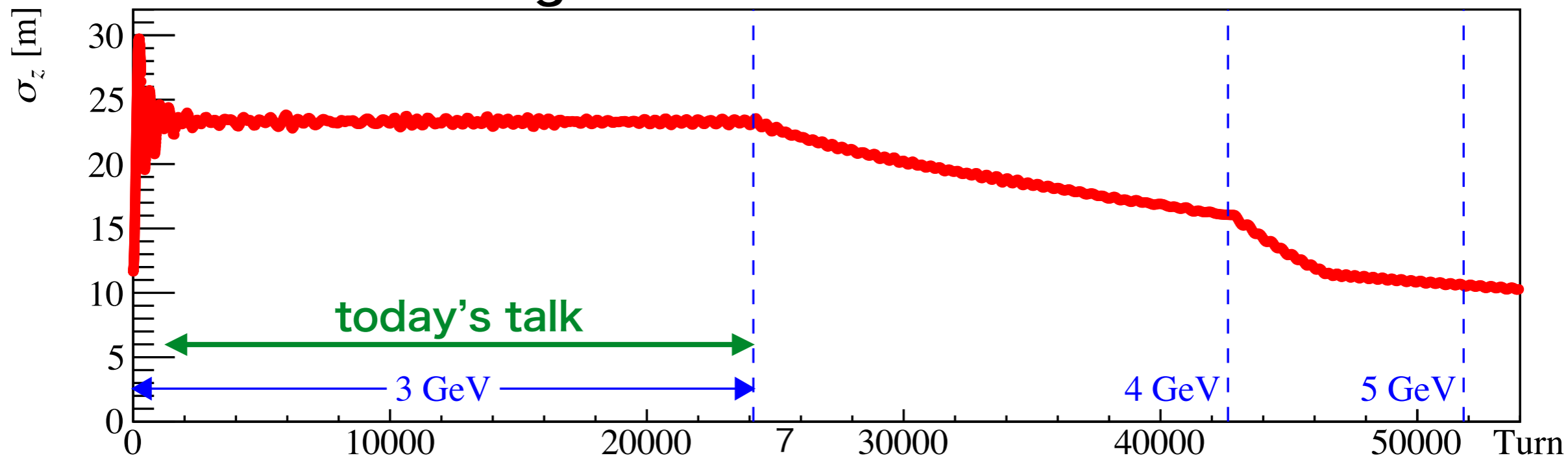
(T. Yasui and Y. Kurimoto, PRAB **25**, 121001 (2022) + some FMA results)

Beam loss & beam size (simulation)

Beam loss



Longitudinal rms beam size

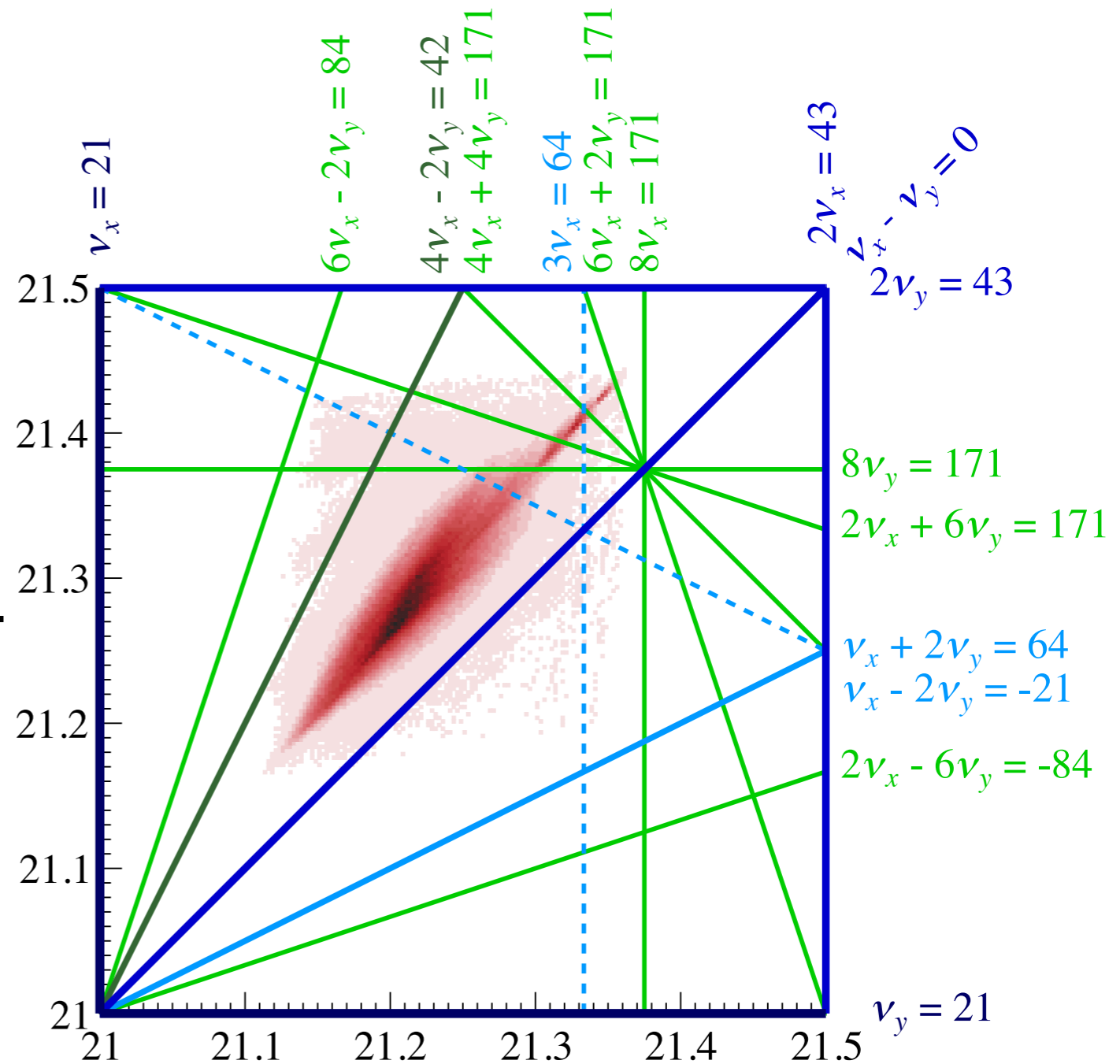


Tune spread and resonances

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 : 2.66×10^{14} ppp

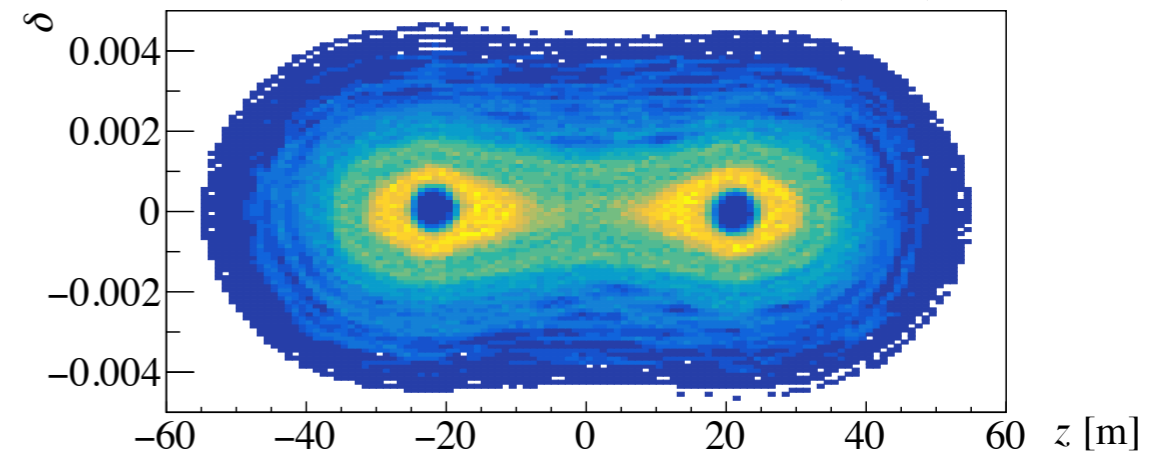
Outline

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

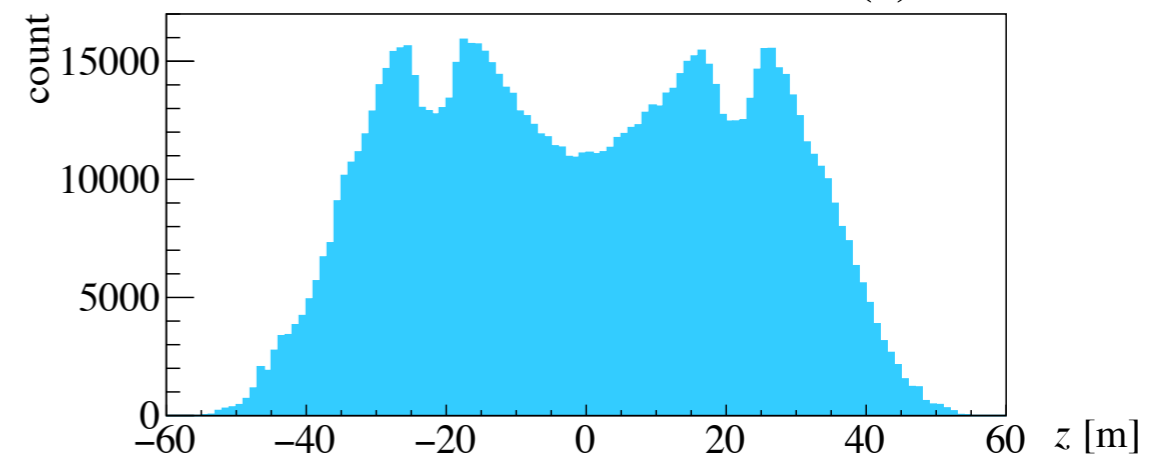
Longitudinal distribution

2nd harmonic RF cavities are used for peak suppression.

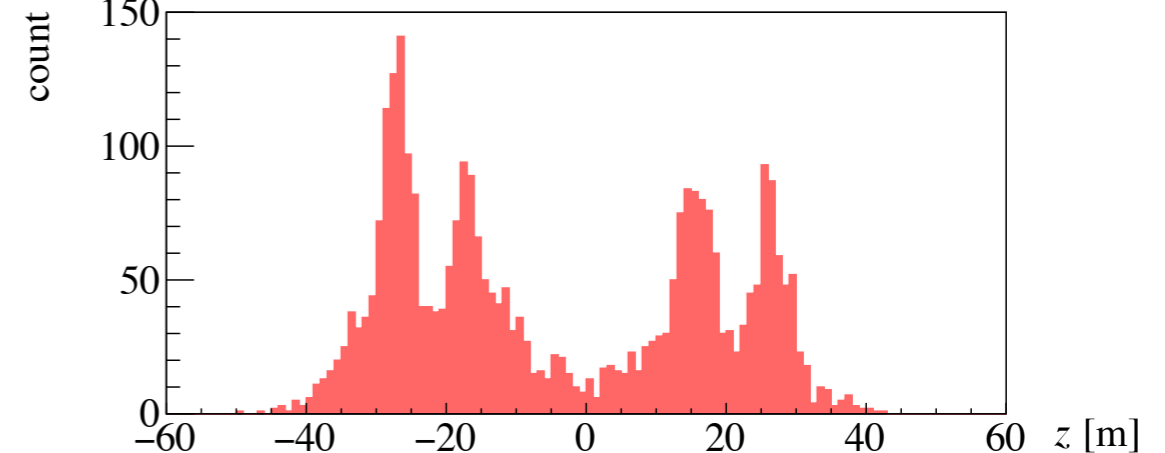
Beam distribution (z, δ)



Beam distribution (z)



Lost particles distribution (z)



Longitudinal distribution

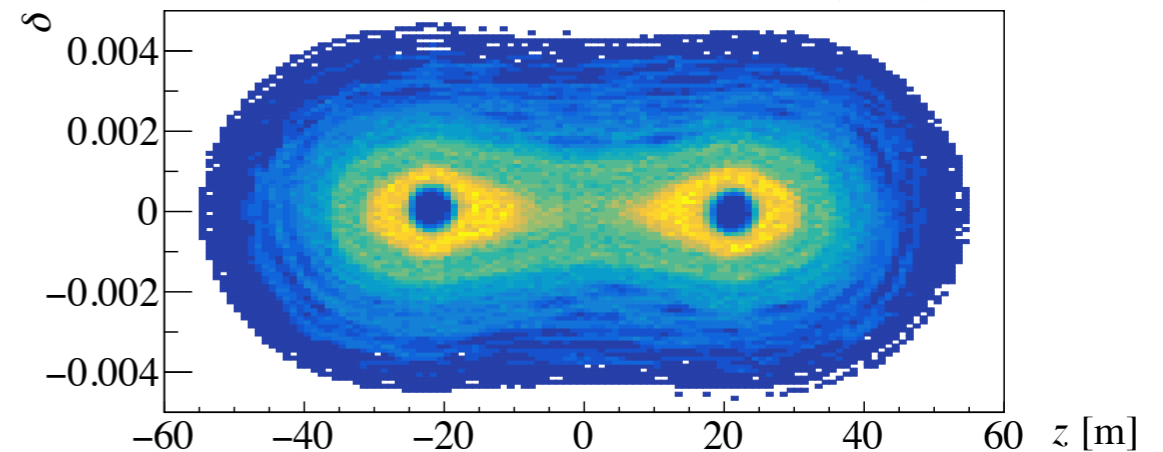
2nd harmonic RF cavities are used for peak suppression.

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

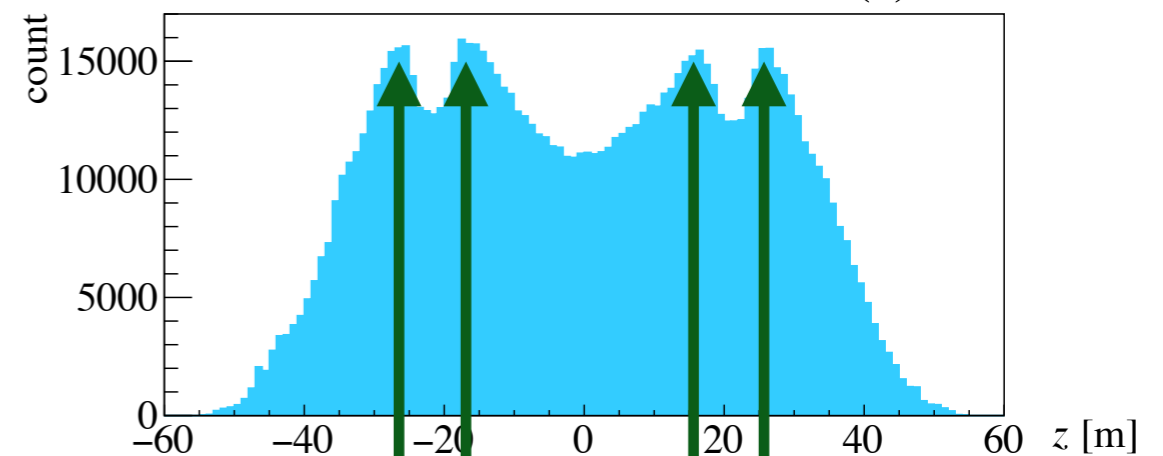
Beam loss is caused by space charge effect.

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

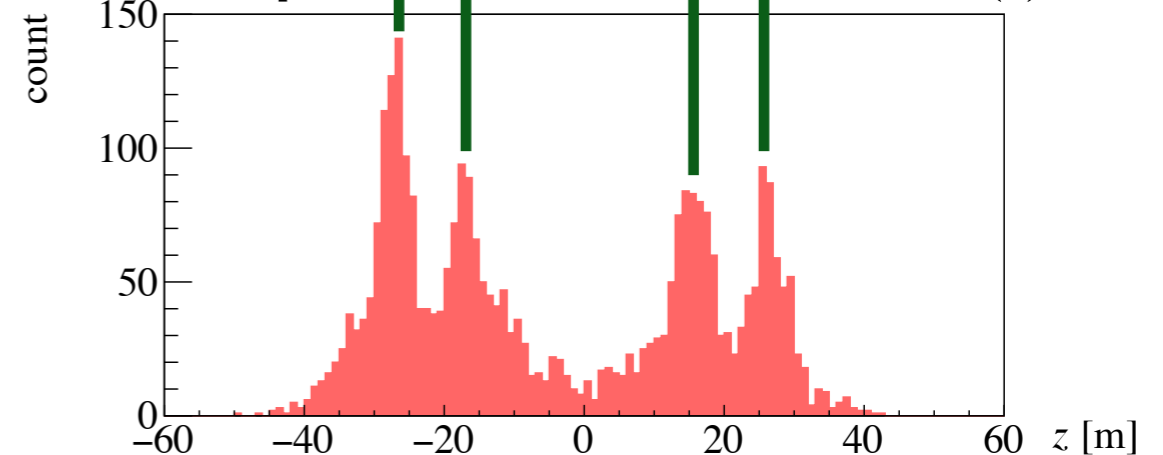
Beam distribution (z, δ)



Beam distribution (z)



Lost particles distribution (z)

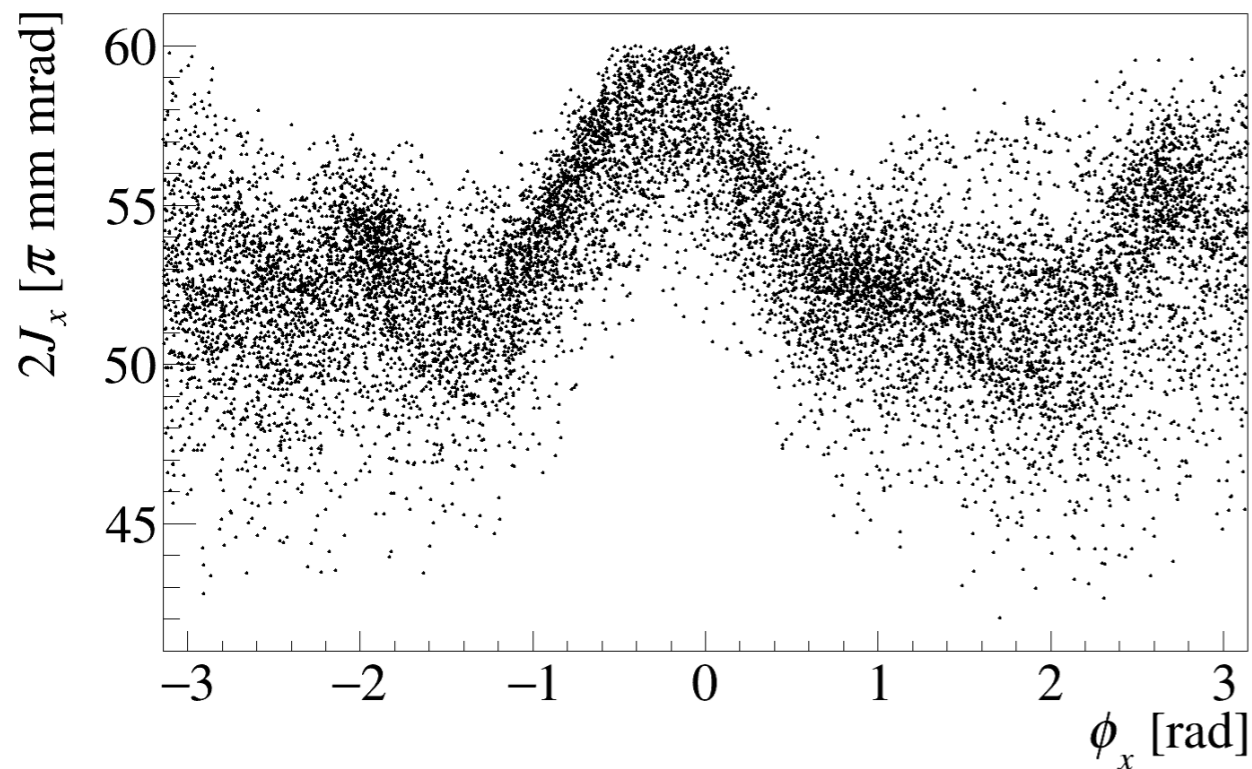


Transverse distribution

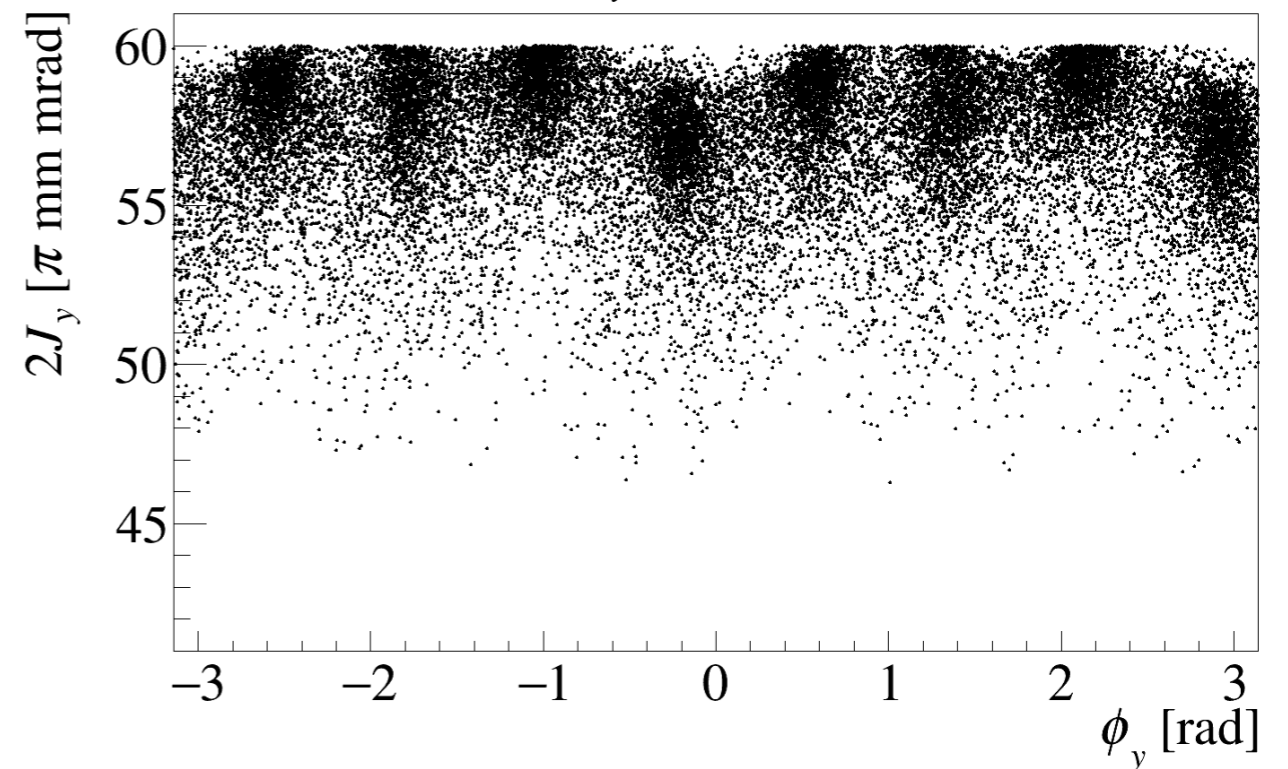
The collimators were set to $(2J_x, 2J_y) = (60\pi, 60\pi)$ mm mrad.

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%)

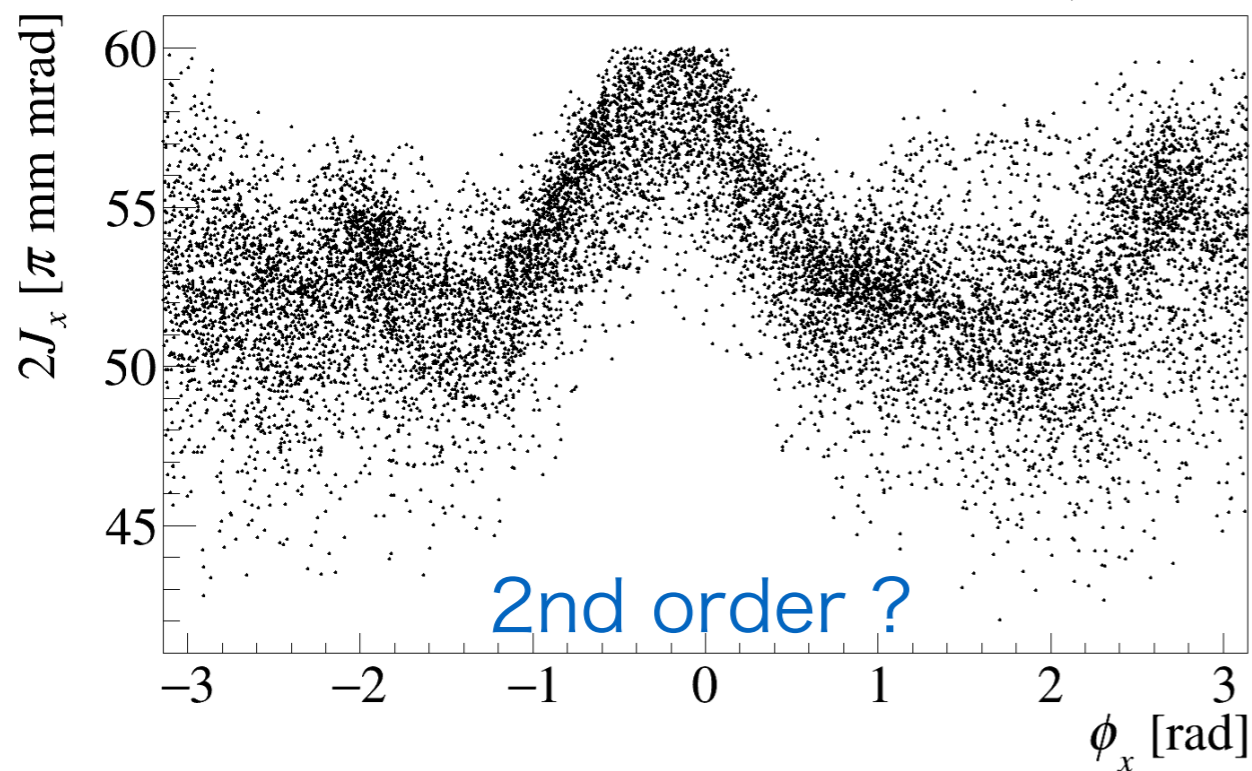


Transverse distribution

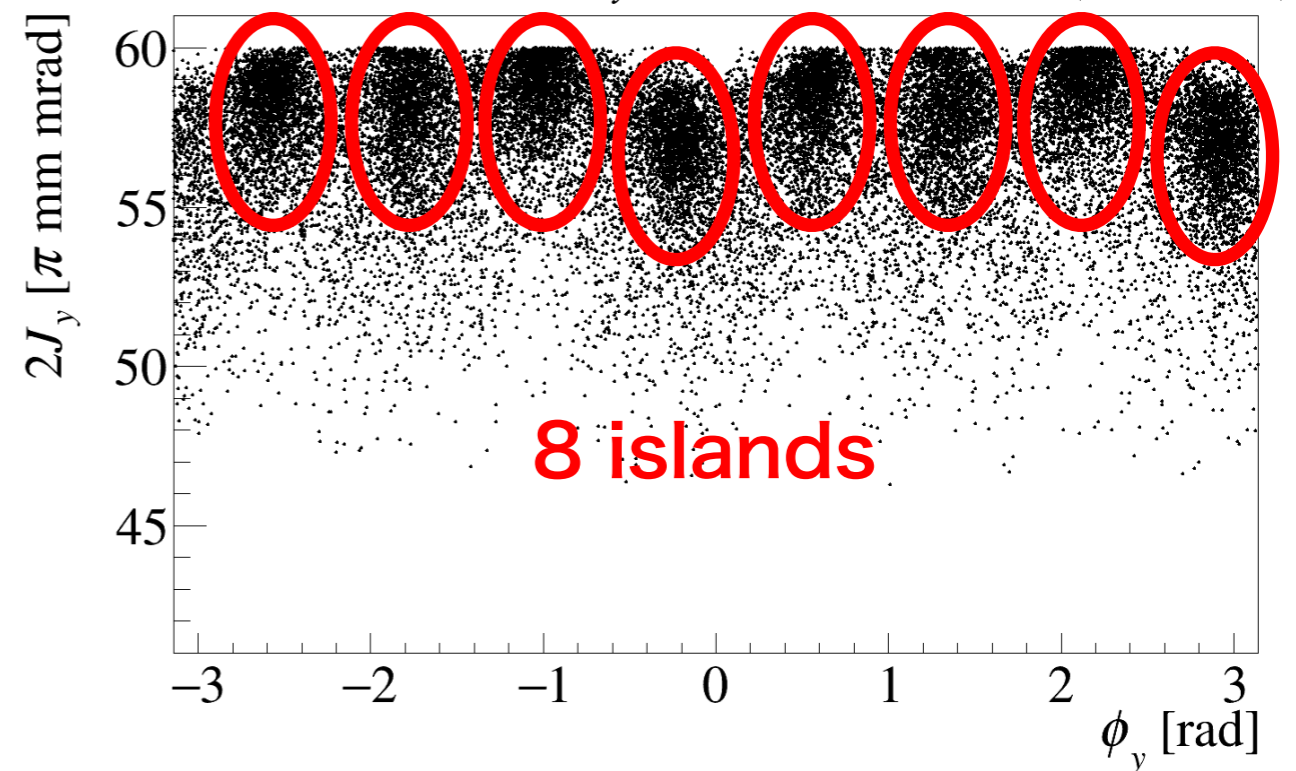
The collimators were set to $(2J_x, 2J_y) = (60\pi, 60\pi)$ mm mrad.

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

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

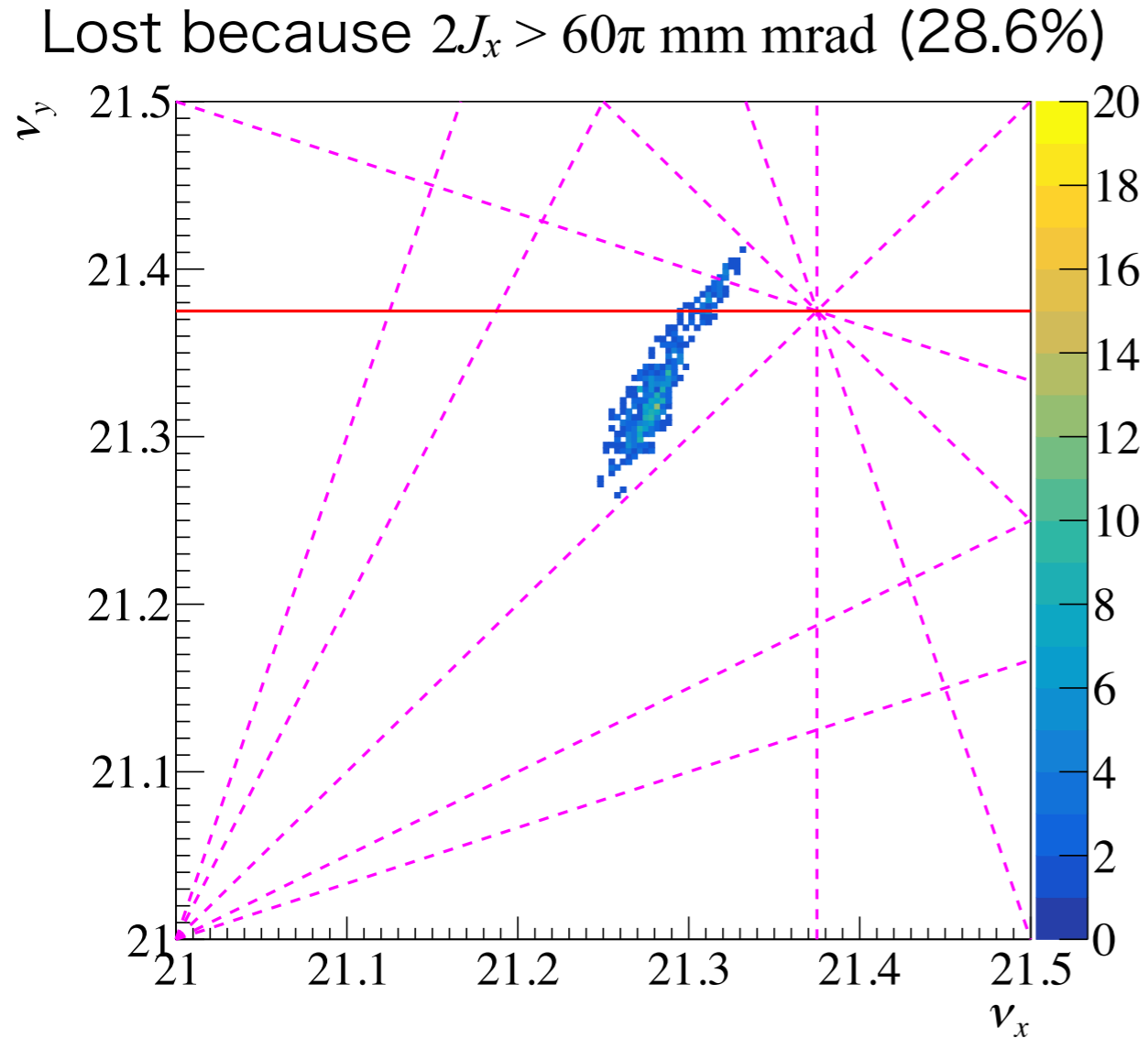


Lost because $2J_y > 60\pi$ mm mrad (71.4%)

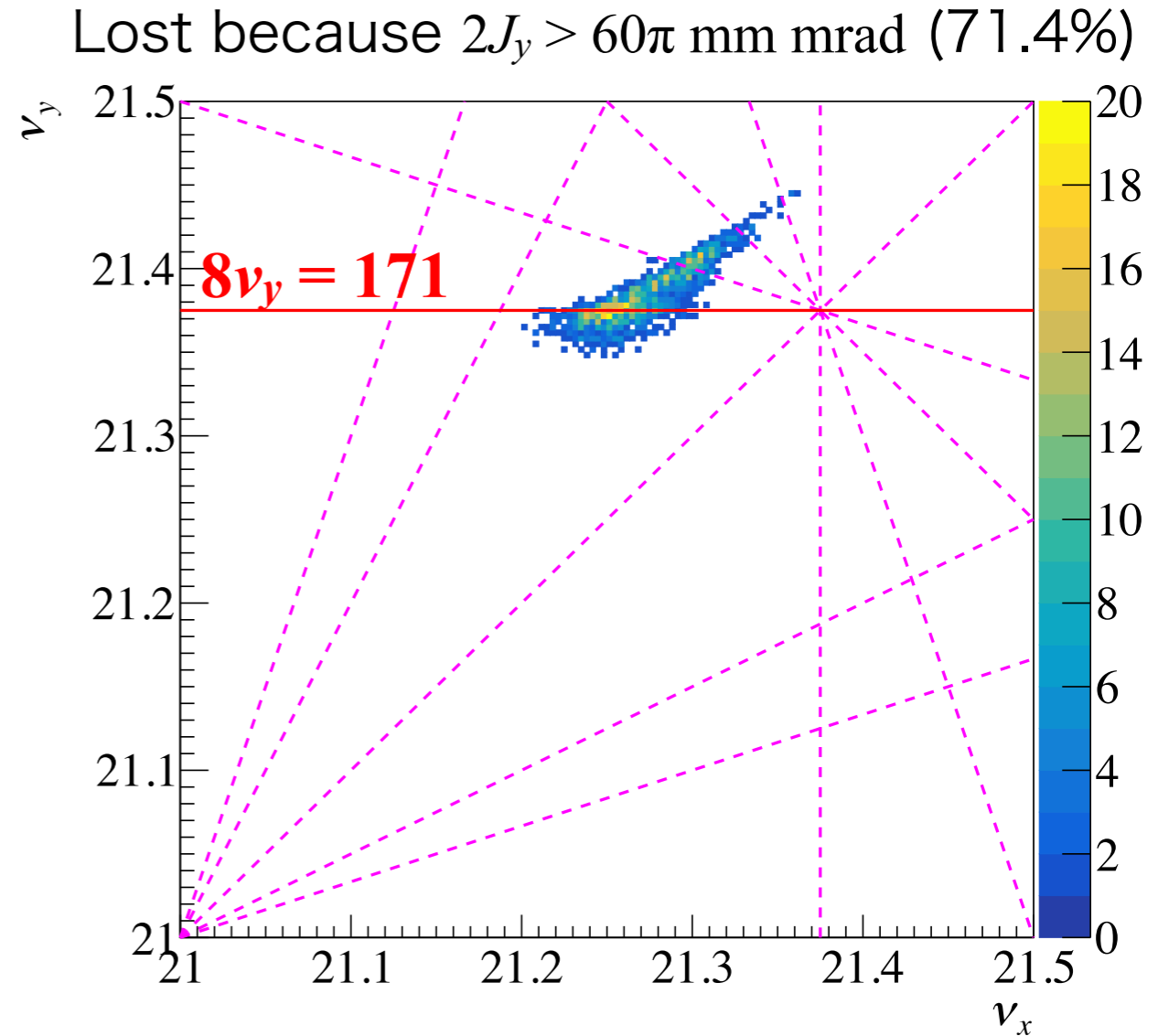


The distribution of the lost particles suggest effects of the resonance $8\nu_y = n$.

Tunes of lost particles



No clear relation
with resonances



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

Outline

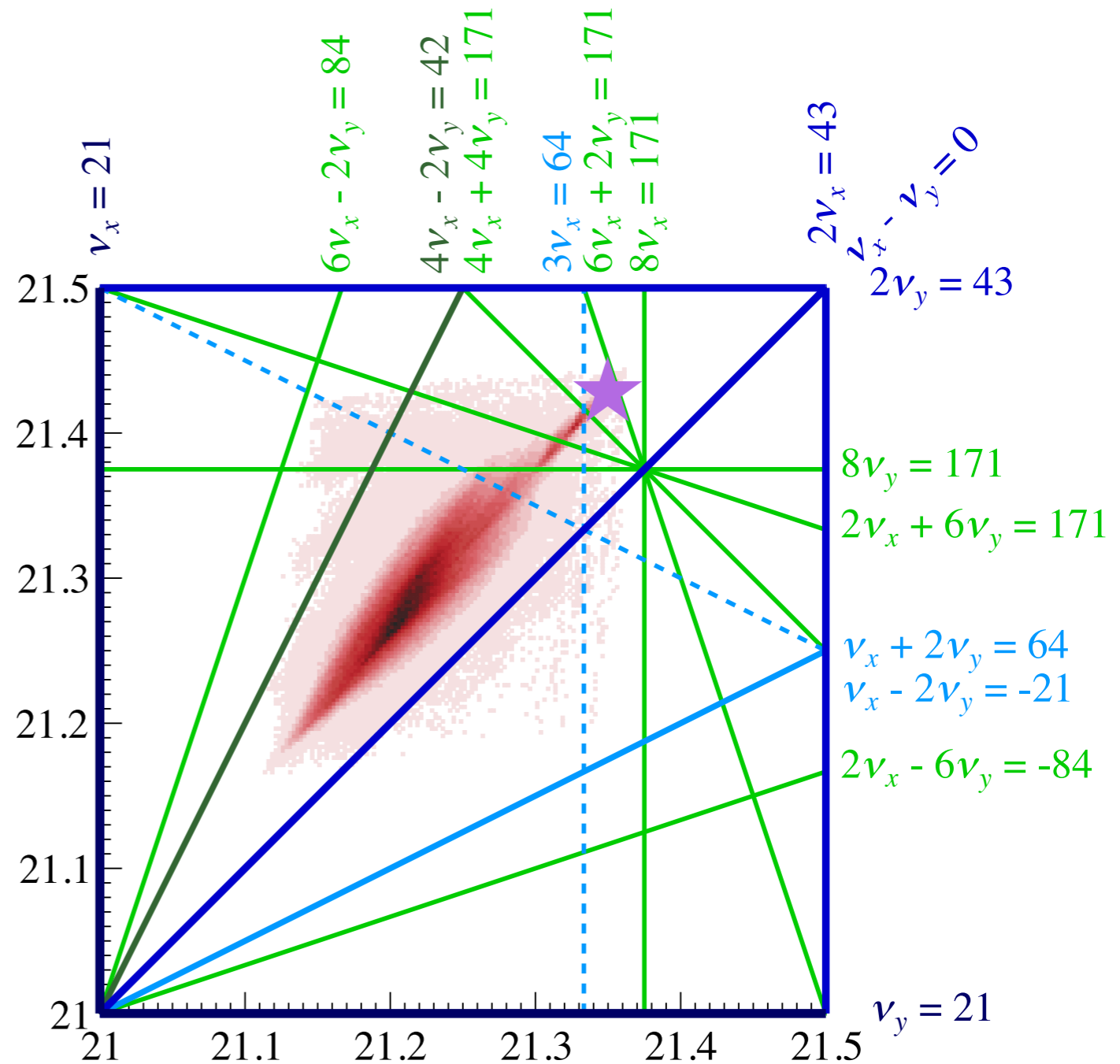
1. Introduction
2. Identification of source of beam loss
- 3. Mechanism of beam loss**
4. A new optics for reducing beam loss
5. Summary

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 $8\nu_y = 171$?

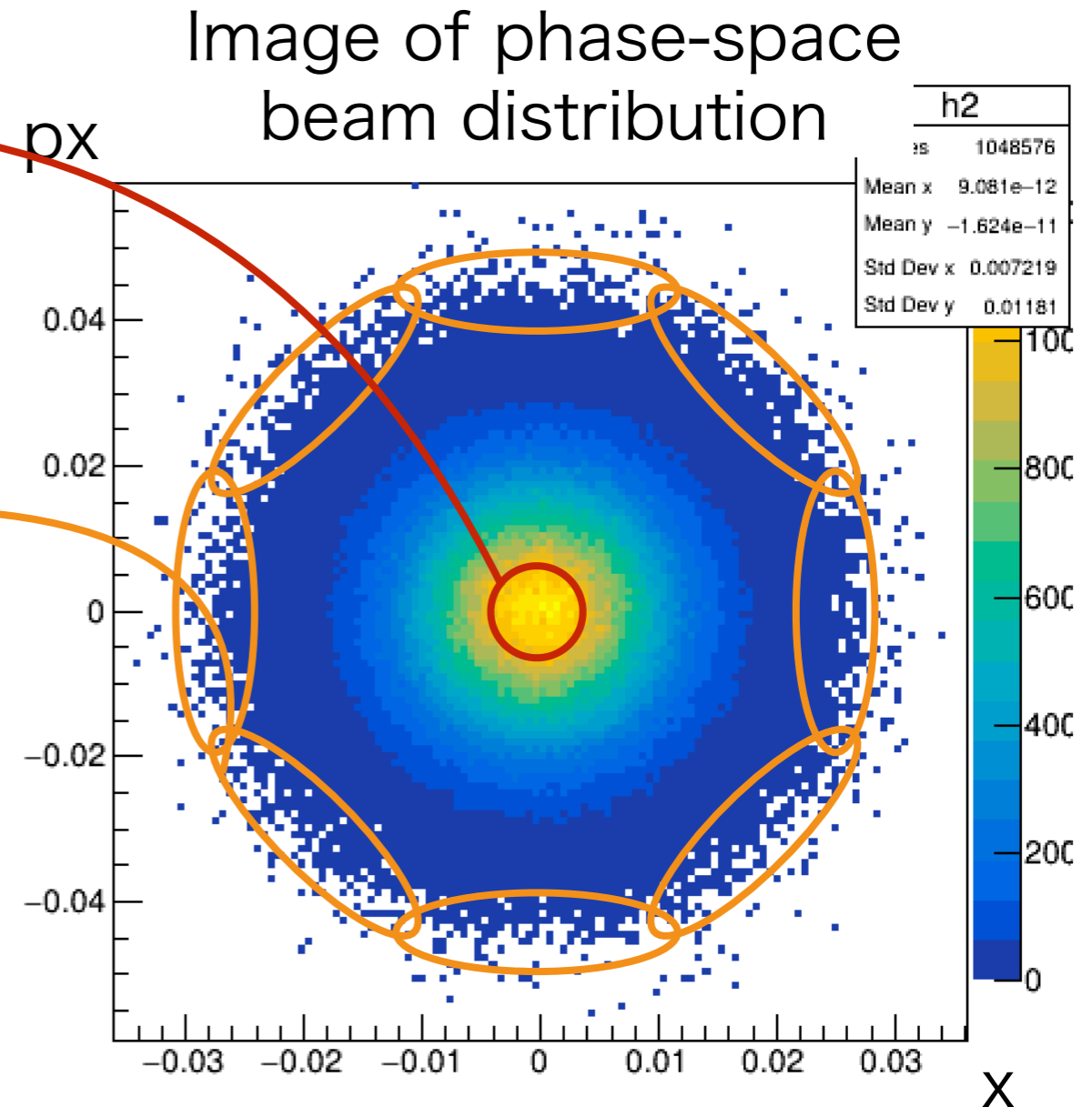


Positions of lost particles

Particles at the center of 6D phase space.
Basically they survive.

Particles at the beam halo of 6D phase space.
These particles may be lost due to resonances.

Beam loss is caused by the resonances which affect particles at beam halo.



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** λ and assuming a Gaussian distribution.

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

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

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

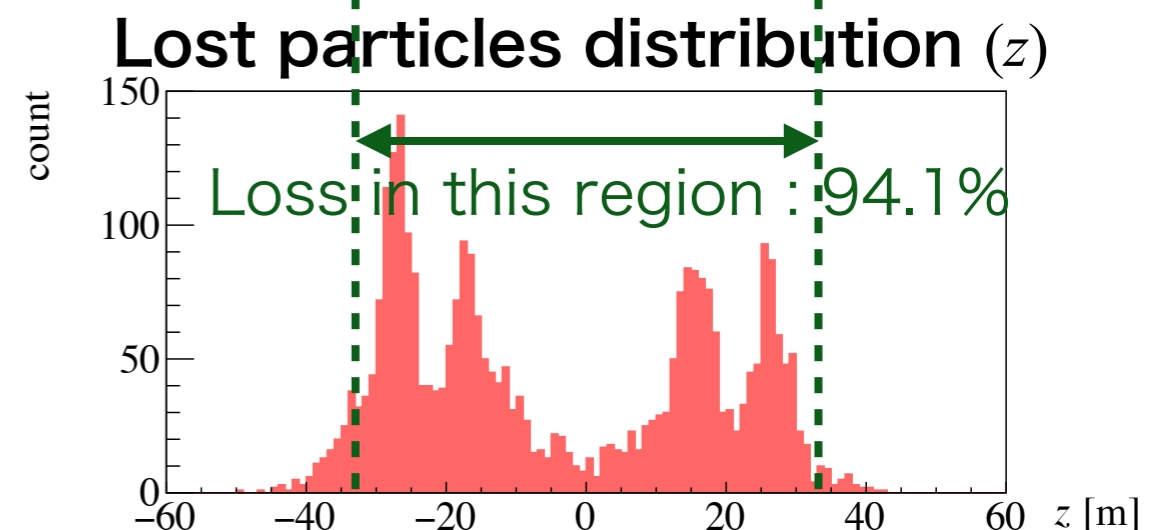
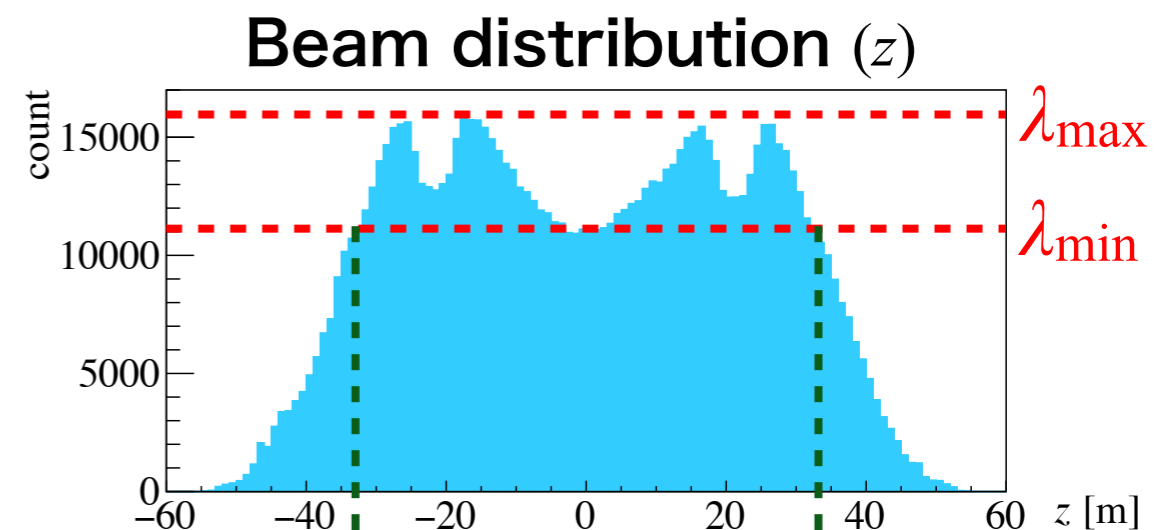
Calculations of incoherent tunes

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

Incoherent tunes can be calculated analytically by setting the **line density** λ and assuming a Gaussian distribution.

Calculations were performed using λ_{max} , λ_{min} .

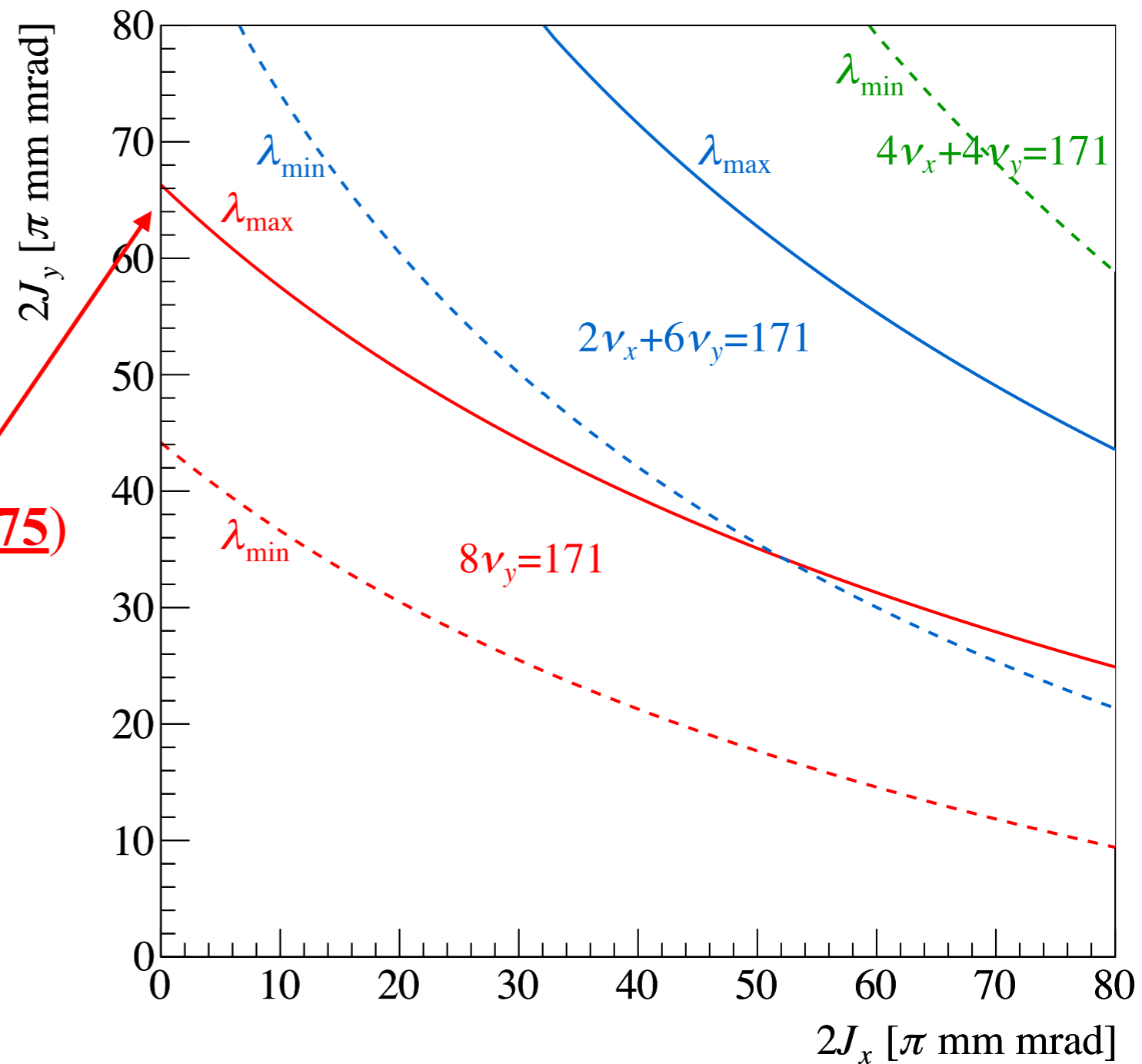
The region $\lambda_{\text{min}} < \lambda < \lambda_{\text{max}}$ ($|z| < 33$ m) covers 94.1% of beam losses.



Where resonances affect

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

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



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:

$$2J_x = 2J_y = 60\pi \text{ mm mrad}$$



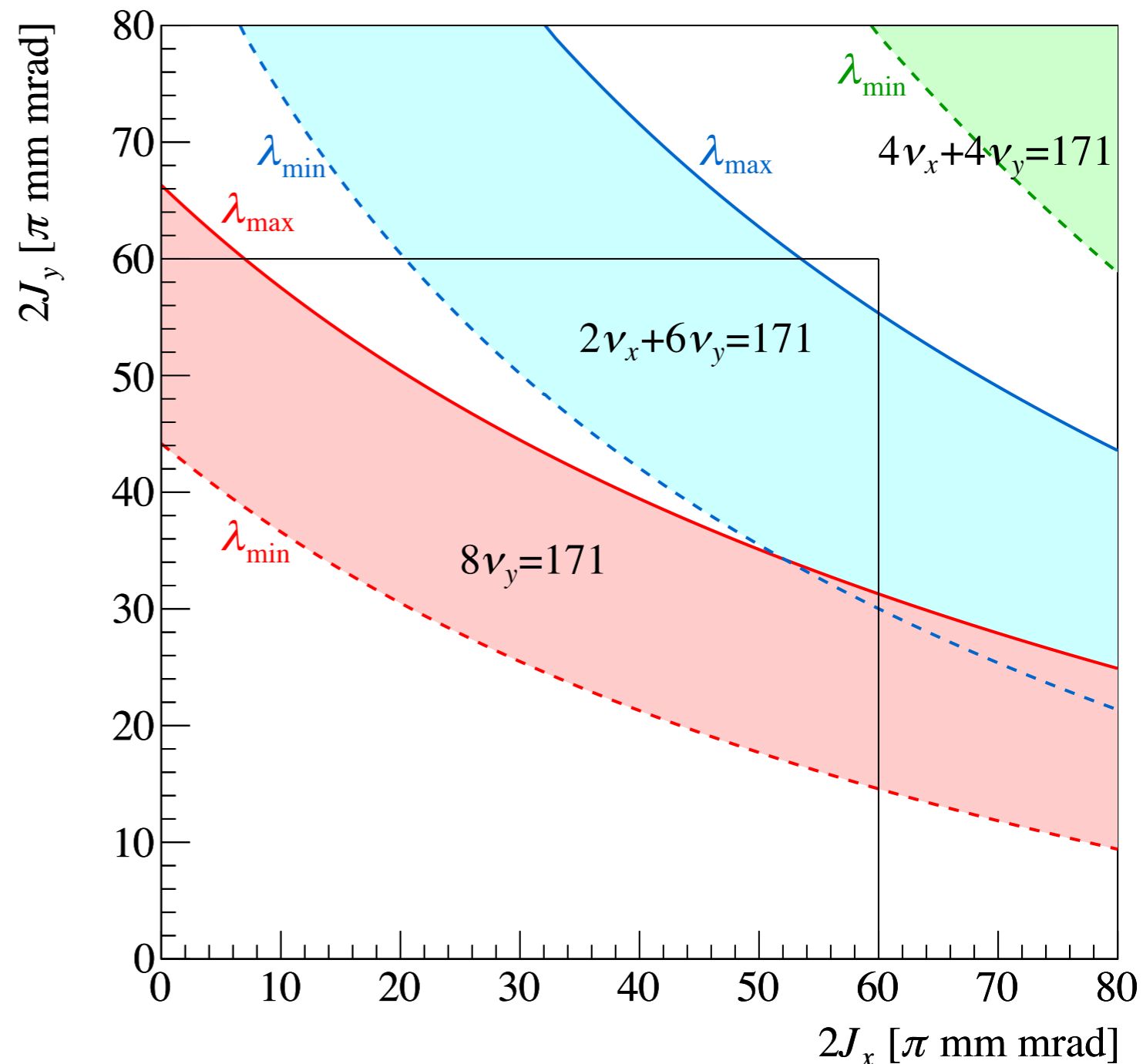
“The beam halo” is also

$$2J_x = 2J_y = 60\pi \text{ mm mrad.}$$

The resonances

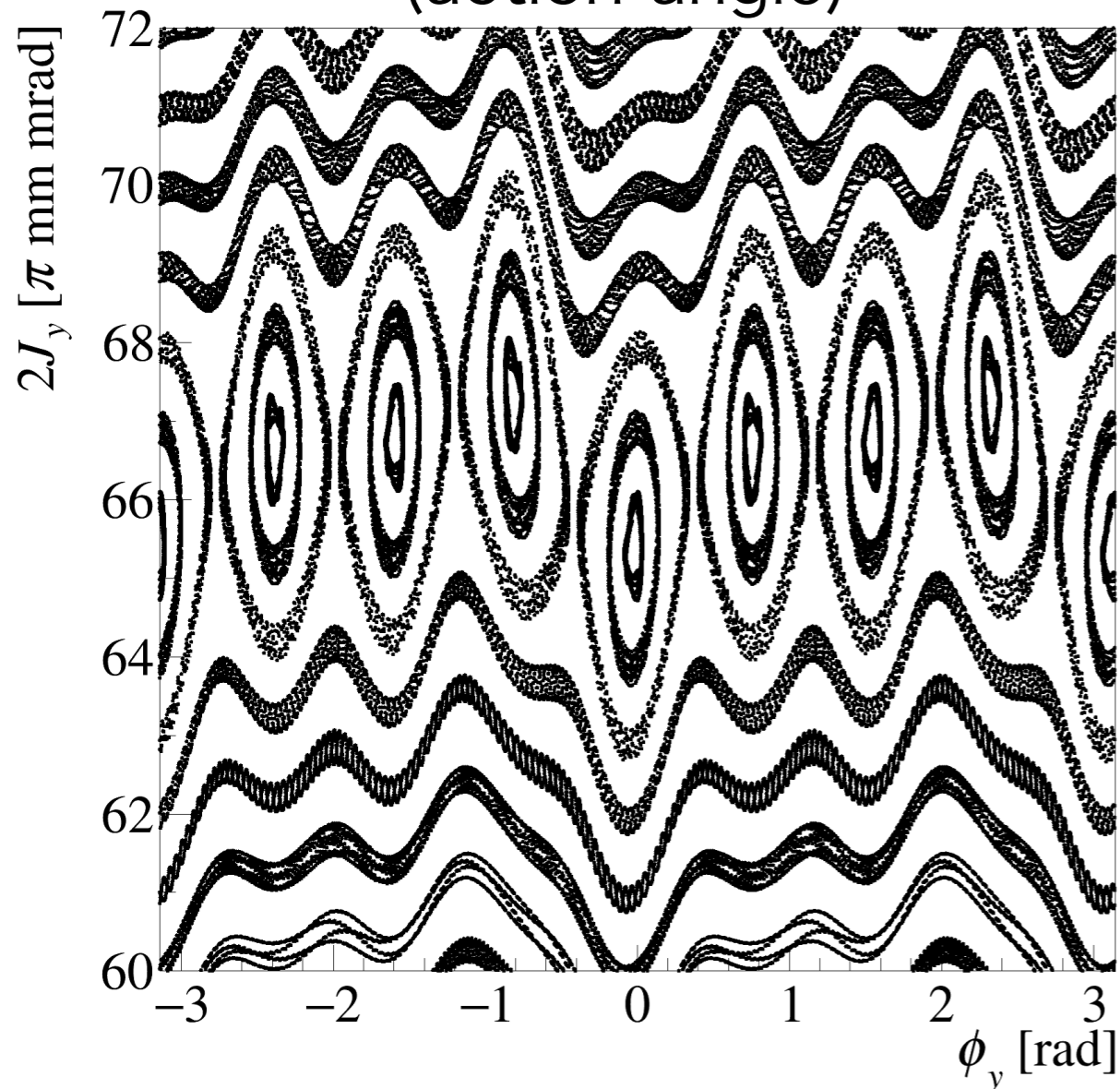
$$8\nu_y = 171 \text{ and } 2\nu_y + 6\nu_x = 171$$

affect $2J_x \sim 2J_y \sim 60\pi \text{ mm mrad}$.



Vertical Poincaré map

Vertical Poincaré map
(action-angle)



Simulation conditions:

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

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

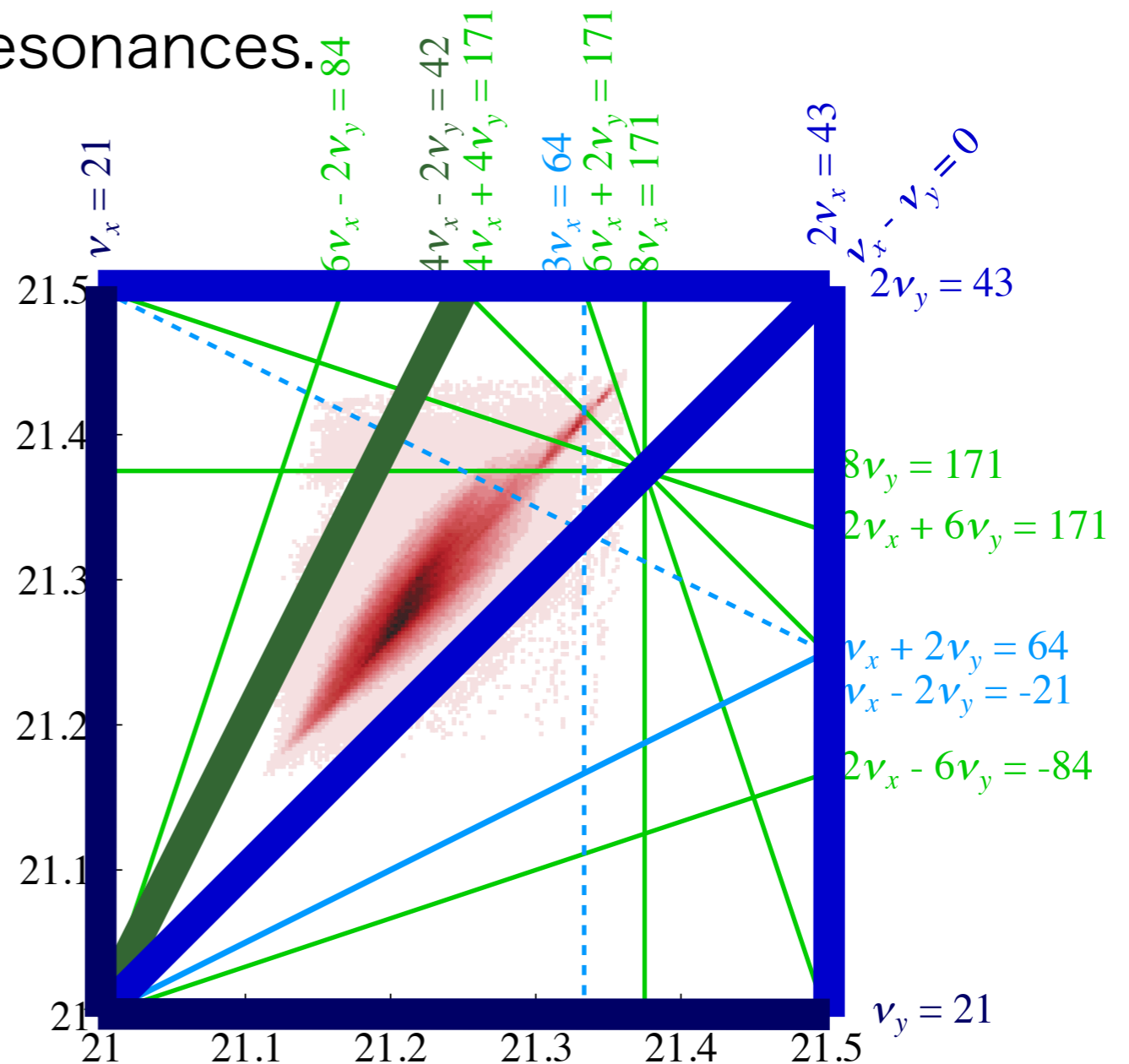
Outline

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

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

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?

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 $U_{m_x, m_y, n}$ 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

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

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

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

phase advance

$$\chi_y(s) = \int_0^s \frac{ds}{\beta_y} \dots \text{changeable}$$

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

$U_{0,8,171}$ 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 ($\Delta\Psi_{\text{arc},x} = 6 \times 2\pi$)
- Better to change globally than locally.

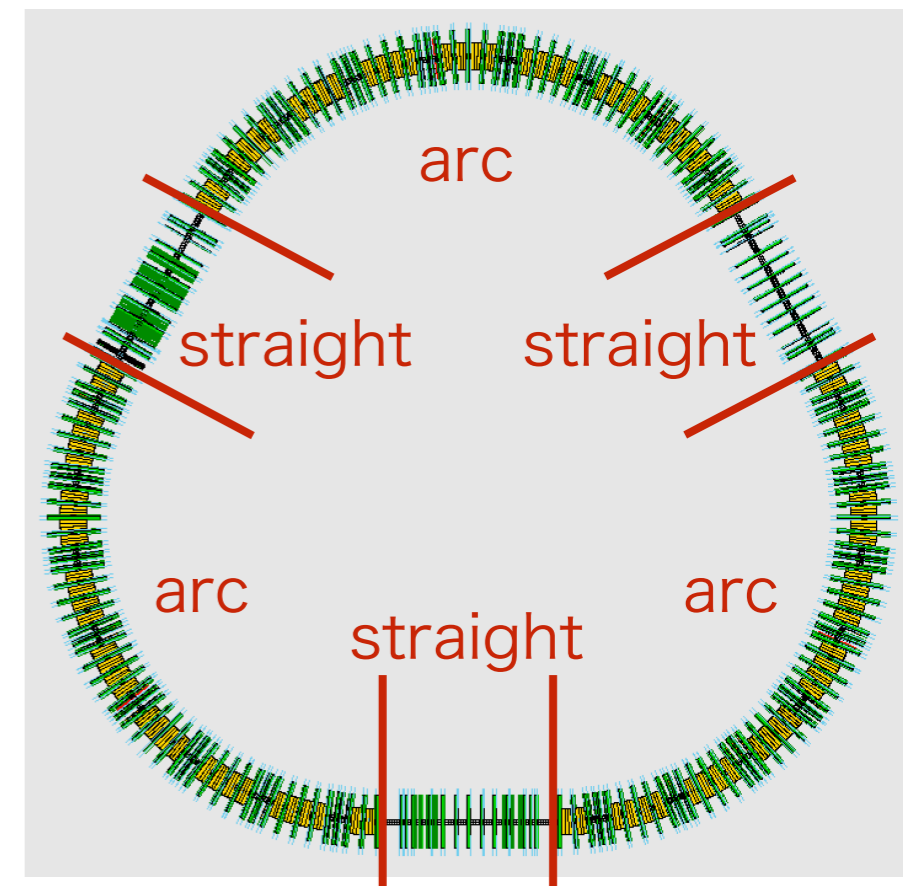


We chose $\Delta\Psi_{\text{arc},y}$ as a scanning knob.

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

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

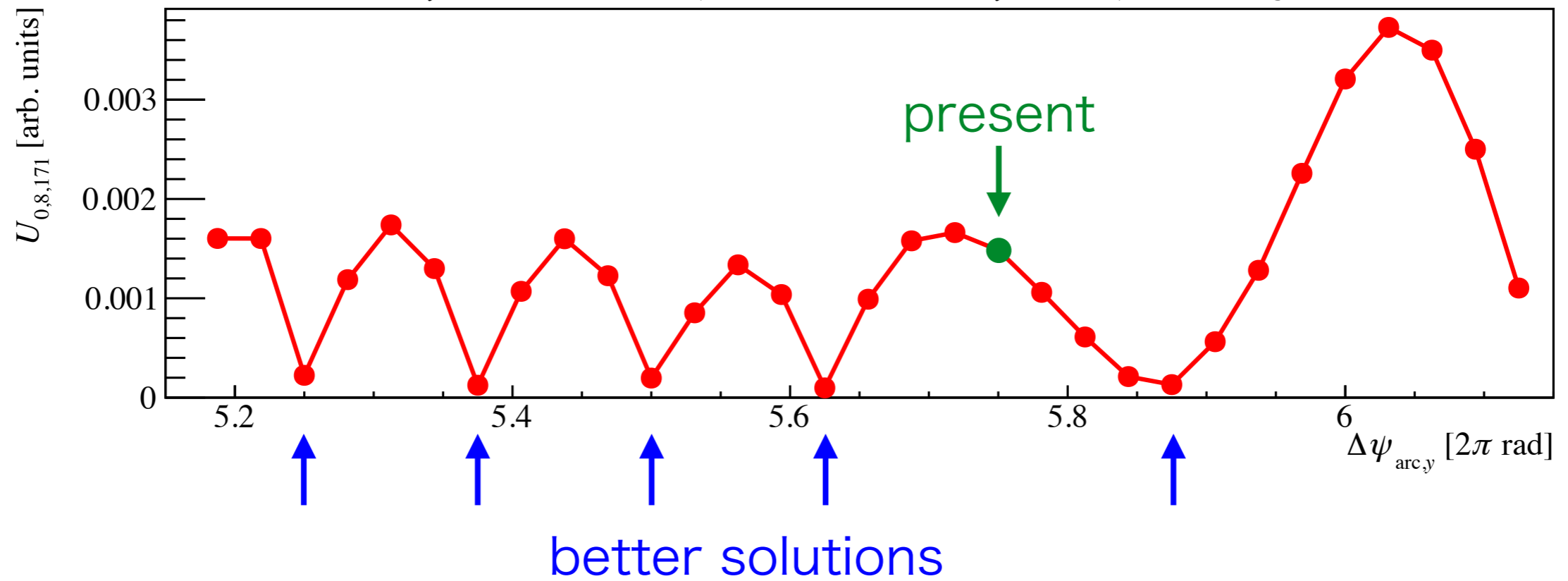
$$\Delta\Psi_{\text{straight},x} = (2\pi\nu_x - 3\Delta\Psi_{\text{arc},x})/3 \quad (\text{fixed})$$



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

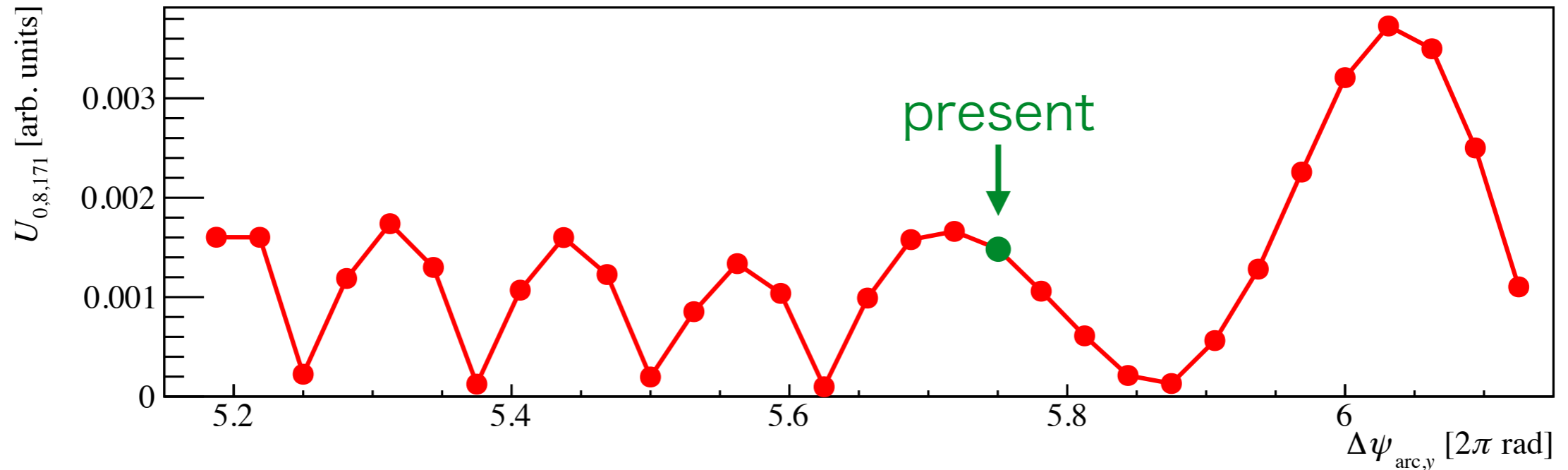
$\Delta\Psi_{\text{arc},y}$ scan

$\Delta\Psi_{\text{arc},y}$ vs $U_{0,8,171}$ ($\lambda=\lambda_{\text{max}}, J_x=0, J_y=66\pi$) (analytical)

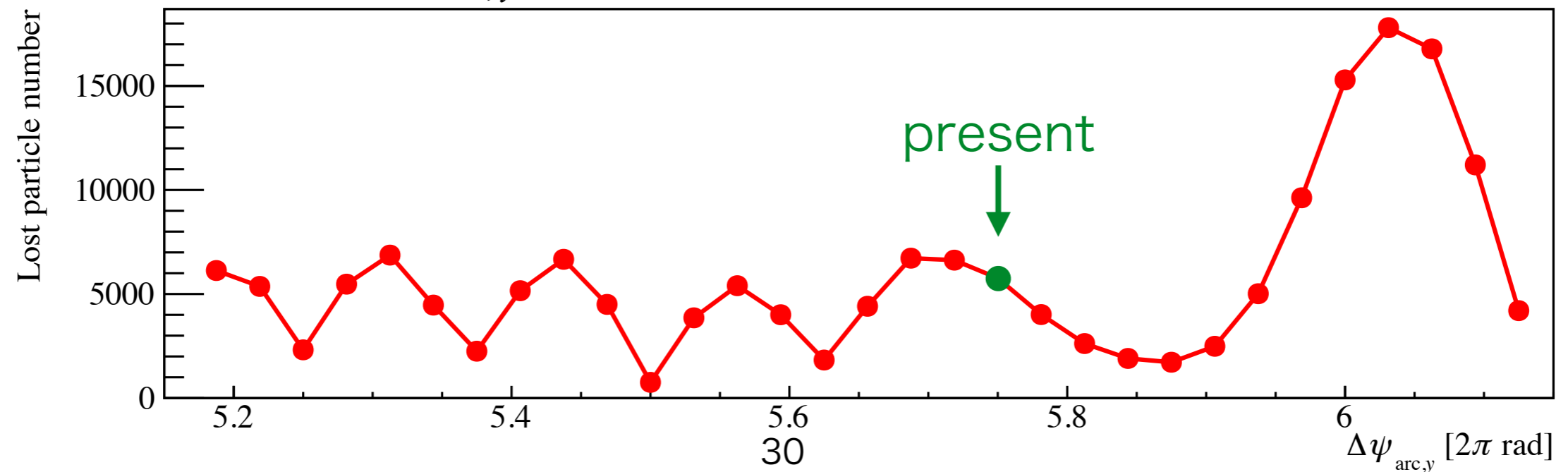


$\Delta\Psi_{\text{arc},y}$ scan

$\Delta\Psi_{\text{arc},y}$ VS $U_{0,8,171}$ ($\lambda=\lambda_{\text{max}}, J_x=0, J_y=66\pi$) (analytical)



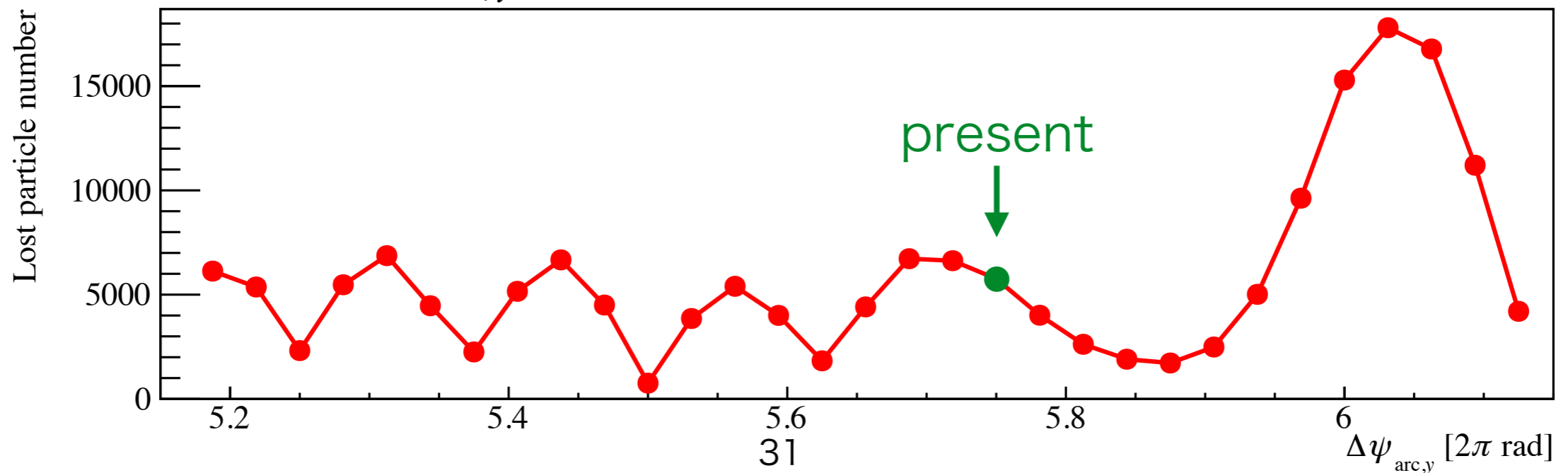
$\Delta\Psi_{\text{arc},y}$ VS **beam loss** (simulation)



$\Delta\Psi_{\text{arc},y}$ scan

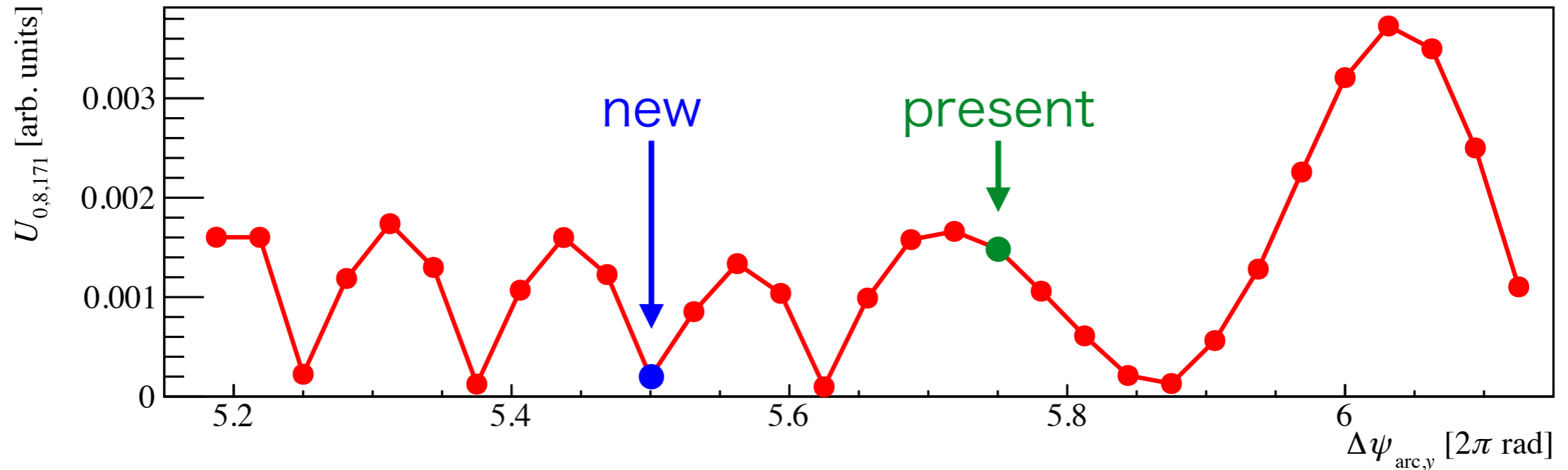


$\Delta\Psi_{\text{arc},y}$ VS **beam loss** (simulation)

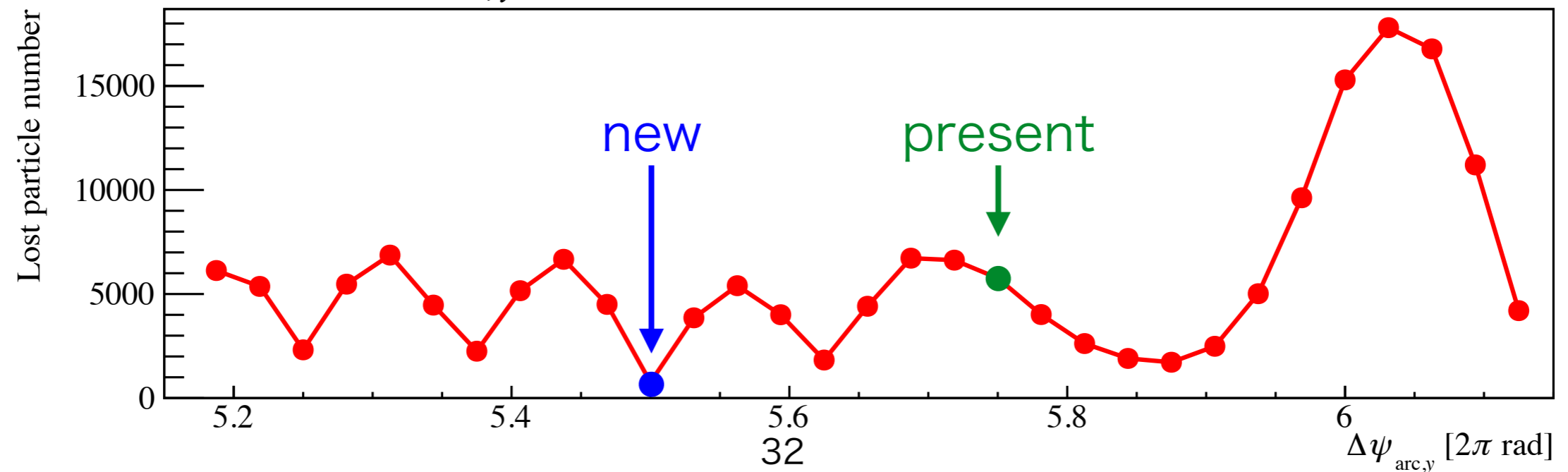


$\Delta\Psi_{\text{arc},y}$ scan

$\Delta\Psi_{\text{arc},y}$ VS $U_{0,8,171}$ ($\lambda=\lambda_{\text{max}}, J_x=0, J_y=66\pi$) (analytical)

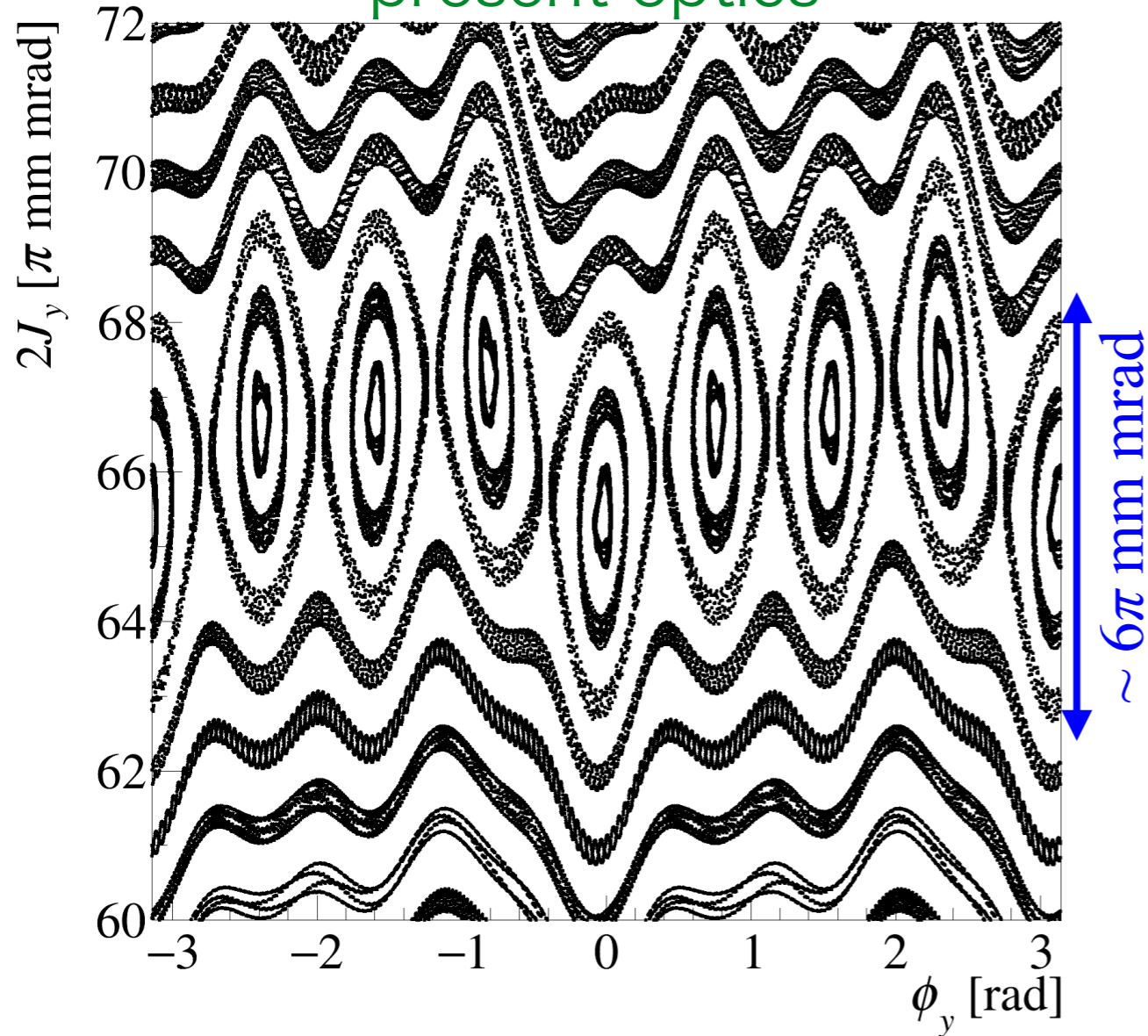


$\Delta\Psi_{\text{arc},y}$ VS **beam loss** (simulation)

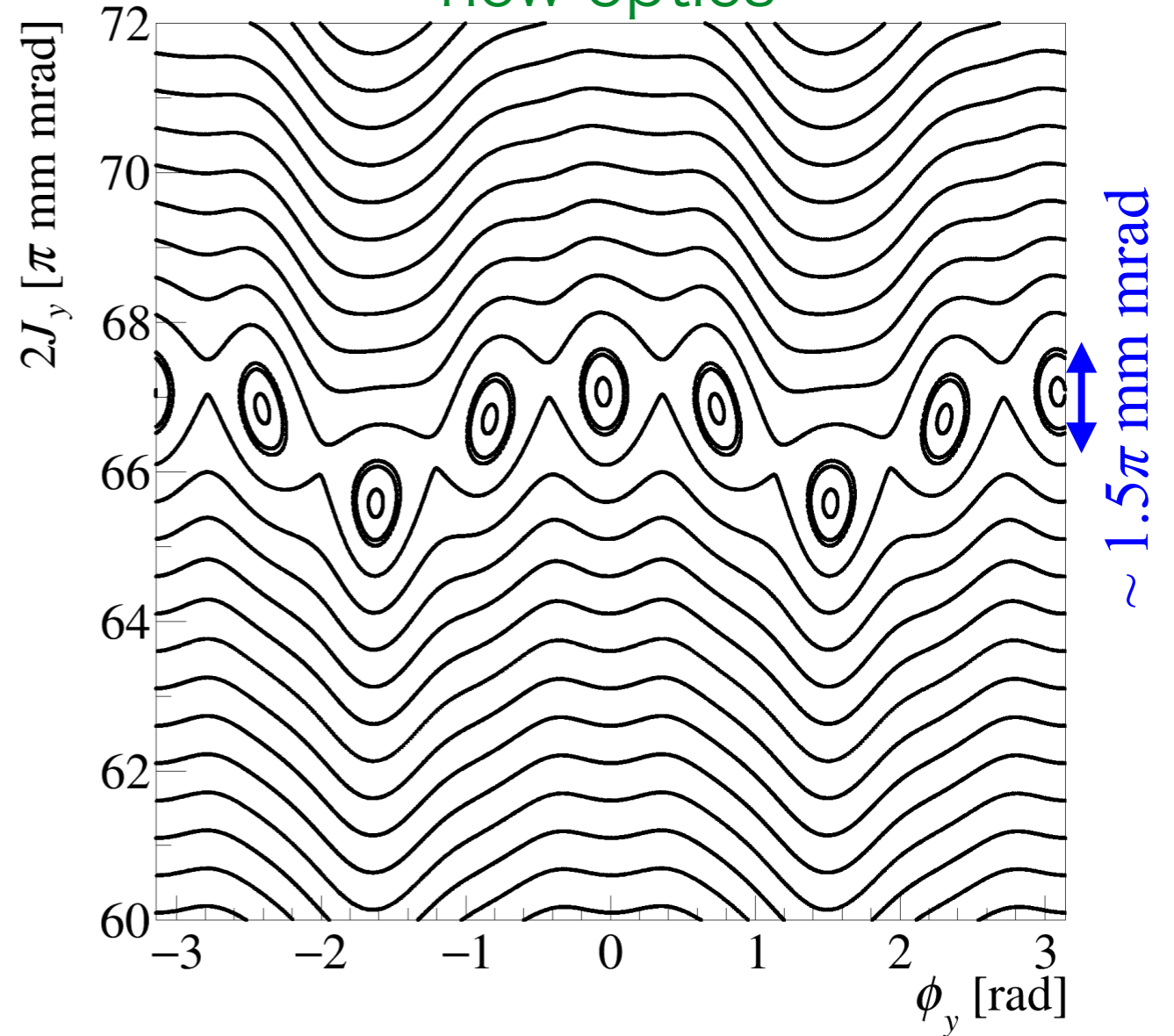


Vertical Poincaré map

present optics



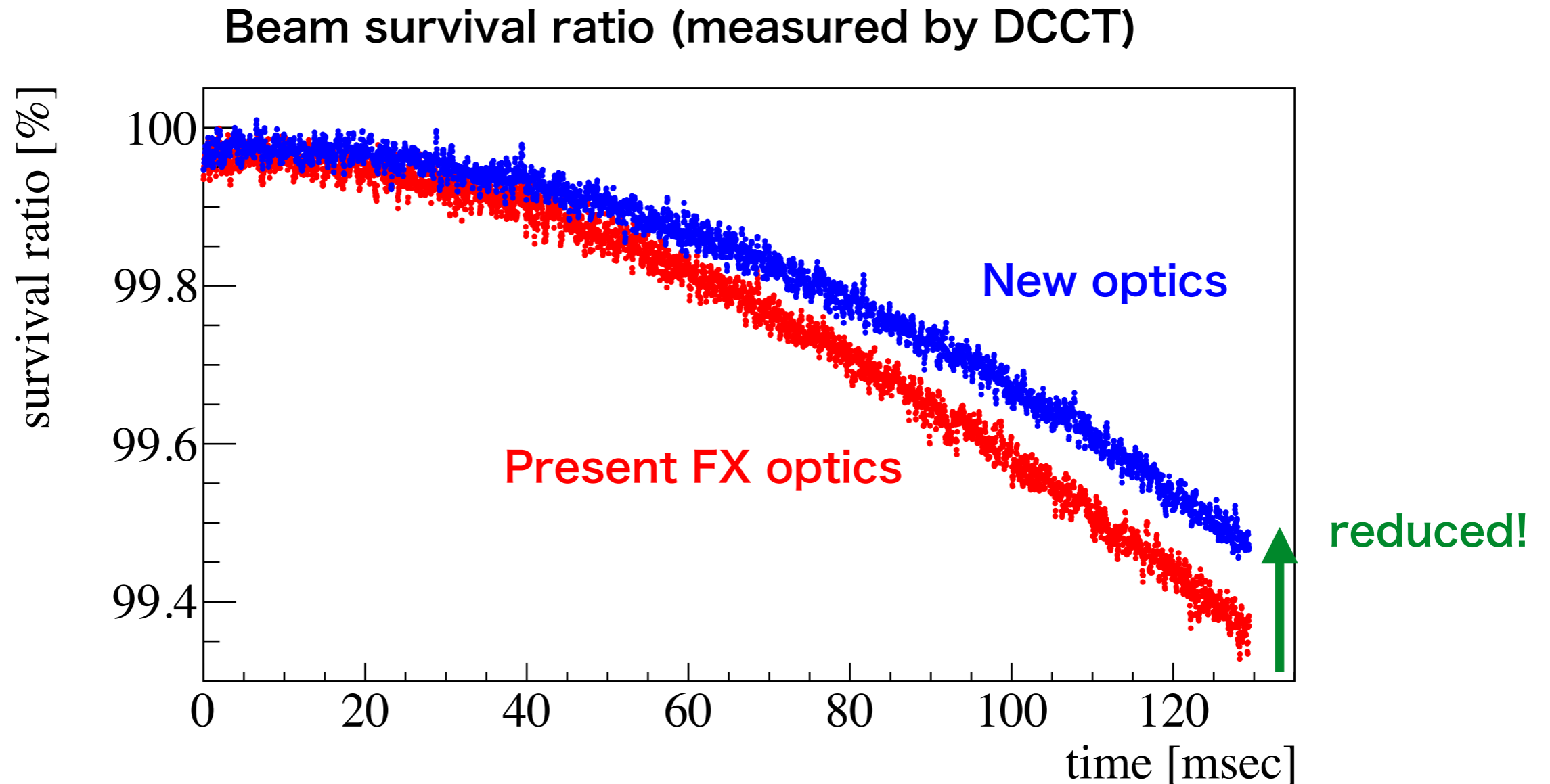
new optics



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

Beam loss measurement

We measured beam losses with the present and new optics.

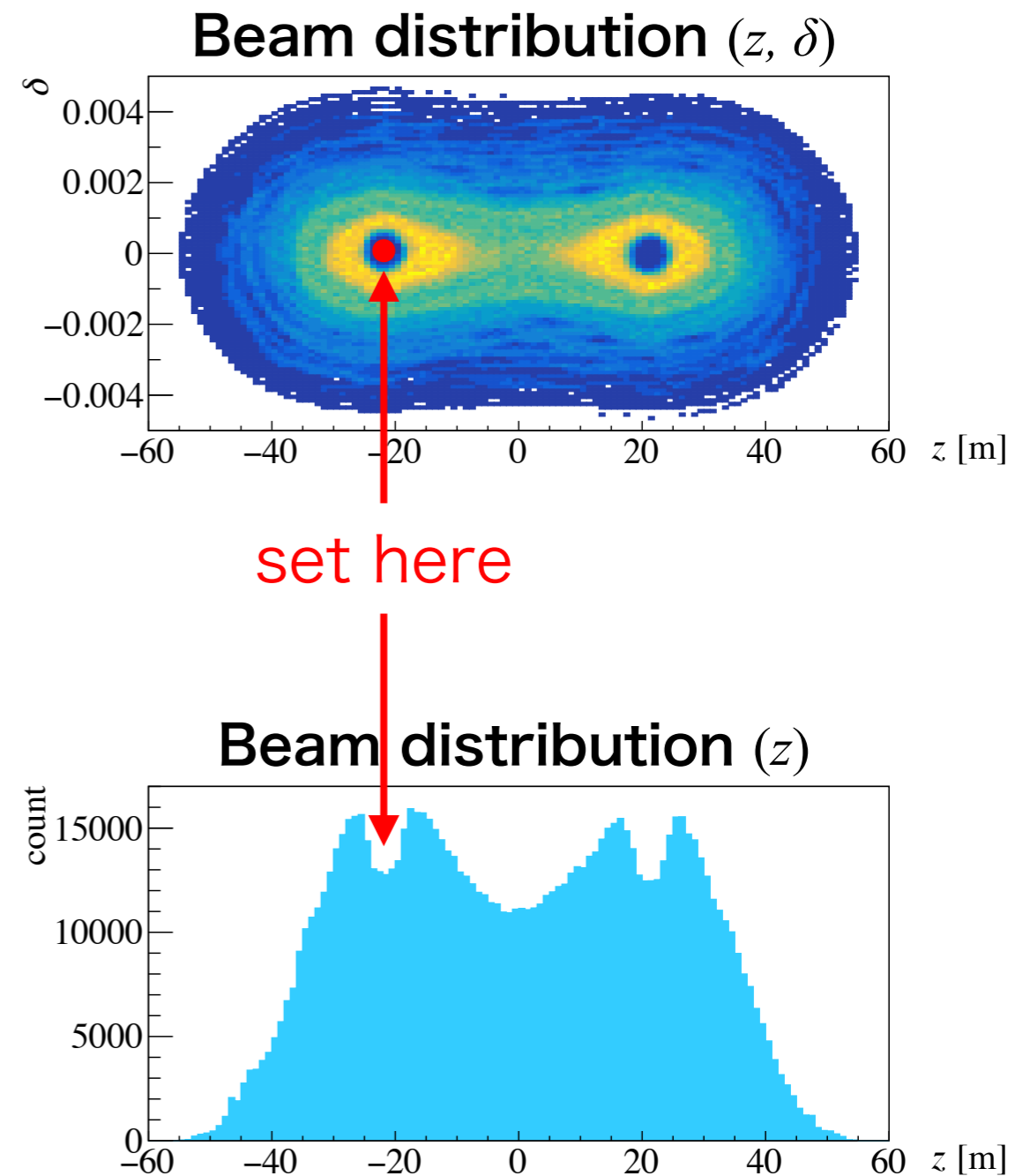


Frequency map analysis

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

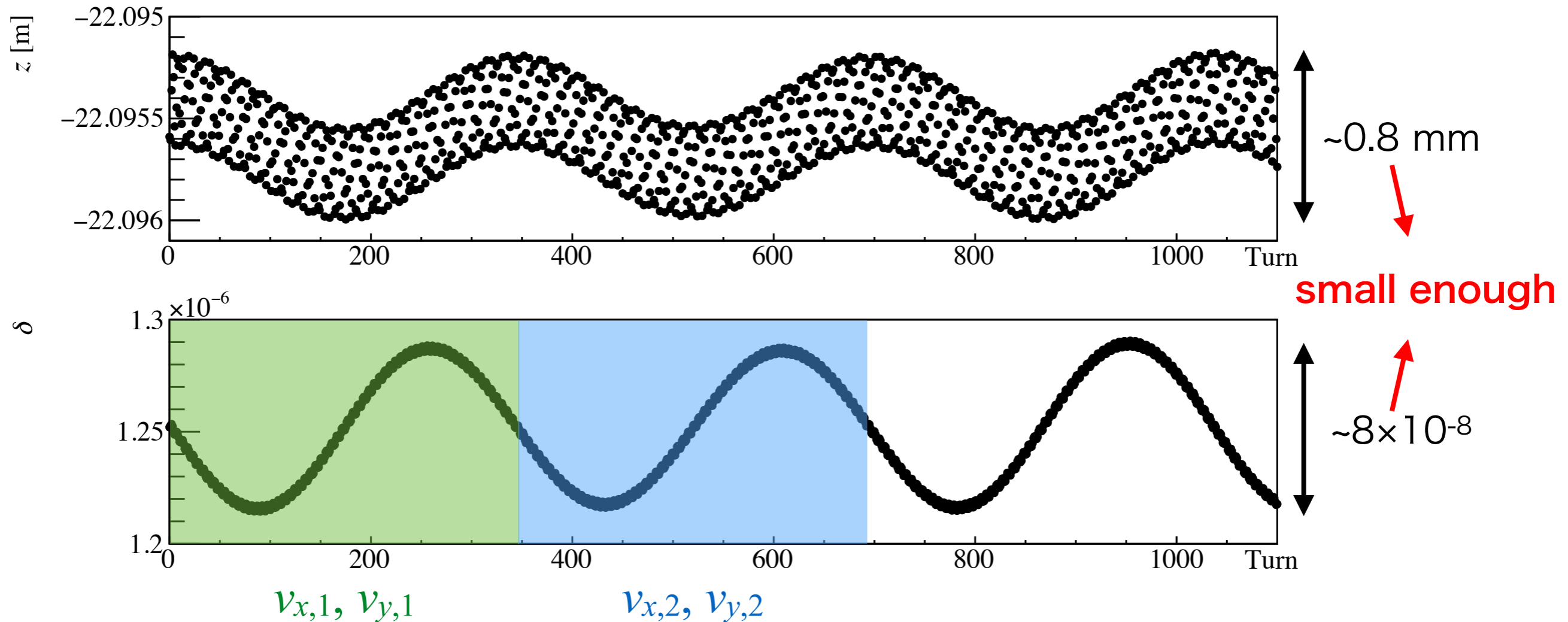
The space charge potentials were constructed by PIC simulation and then fixed (“frozen model”).

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



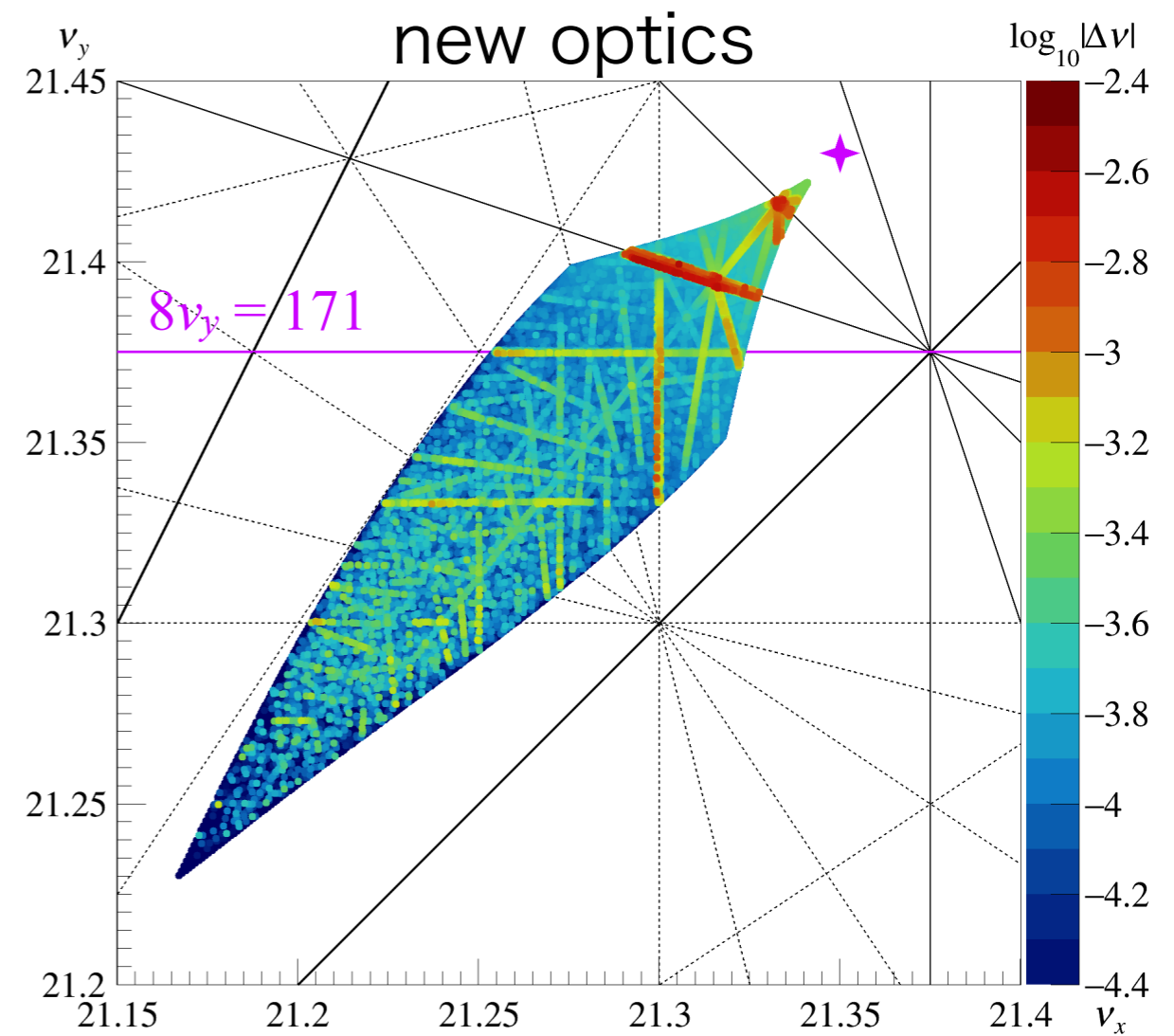
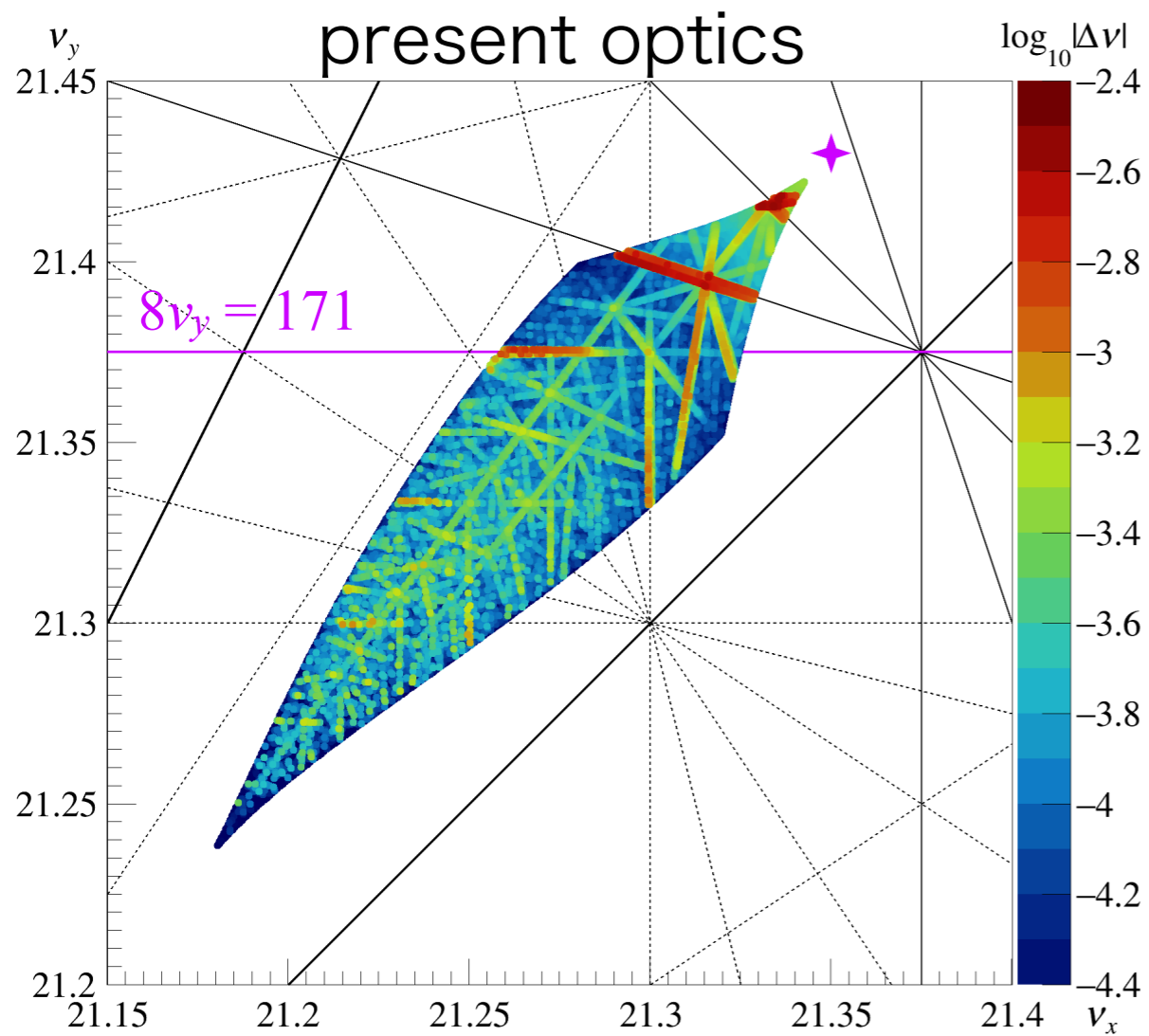
FMA longitudinal motions

Longitudinal positions of the test particle



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 $8v_y = 171$ was also confirmed via FMA.

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**

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.