# 1 MW J-PARC RCS beam operation and further beyond

ICFA

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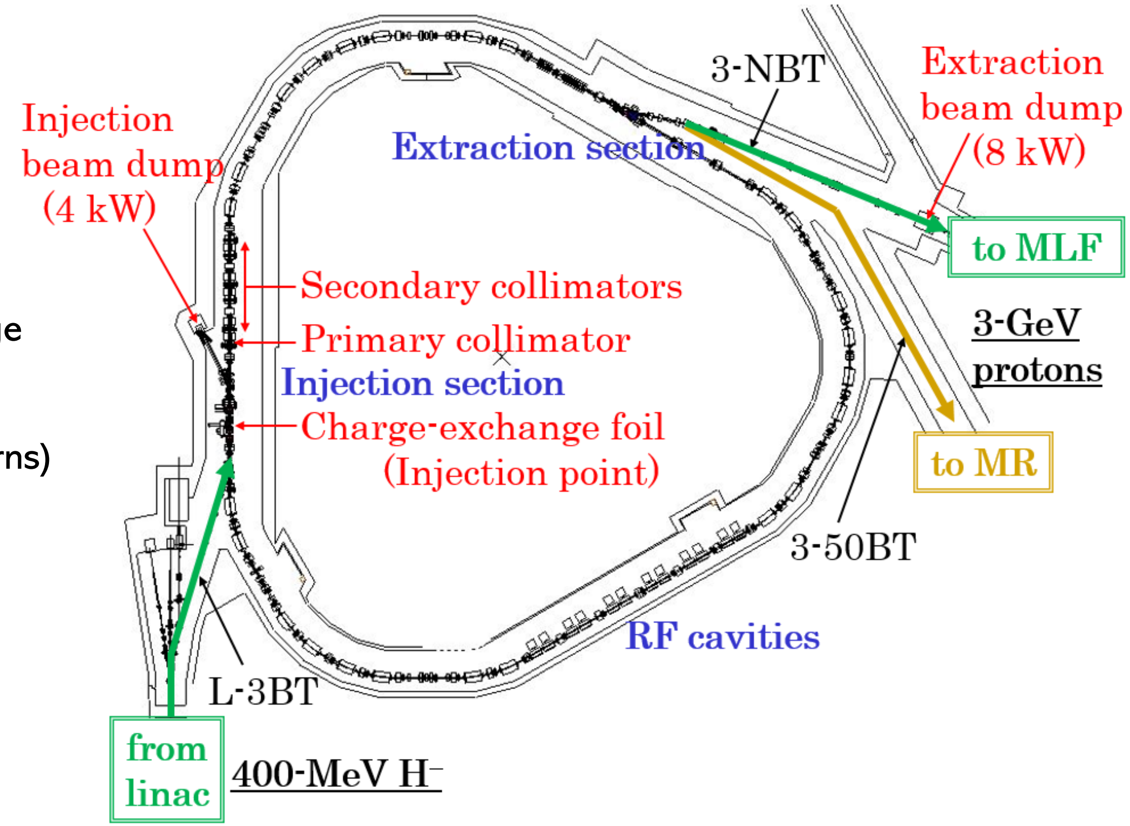
# 1. Introduction

# J-PARC 3-GeV Rapid Cycling Synchrotron (RCS)

| | |
|---|---|
| Circumference | 348.333 m |
| Superperiodicity | 3 |
| Harmonic number | 2 |
| Number of bunches | 2 |
| Injection | Multi-turn, Charge-exchange |
| Injection energy | 400 MeV |
| Injection period | 0.5 ms (307 turns) |
| Injection peak current | 50 mA |
| Extraction energy | 3 GeV |
| Repetition rate | 25 Hz |
| Particles per pulse | 8.33 x $10^{13}$ |
| **Beam power** | **1 MW** |

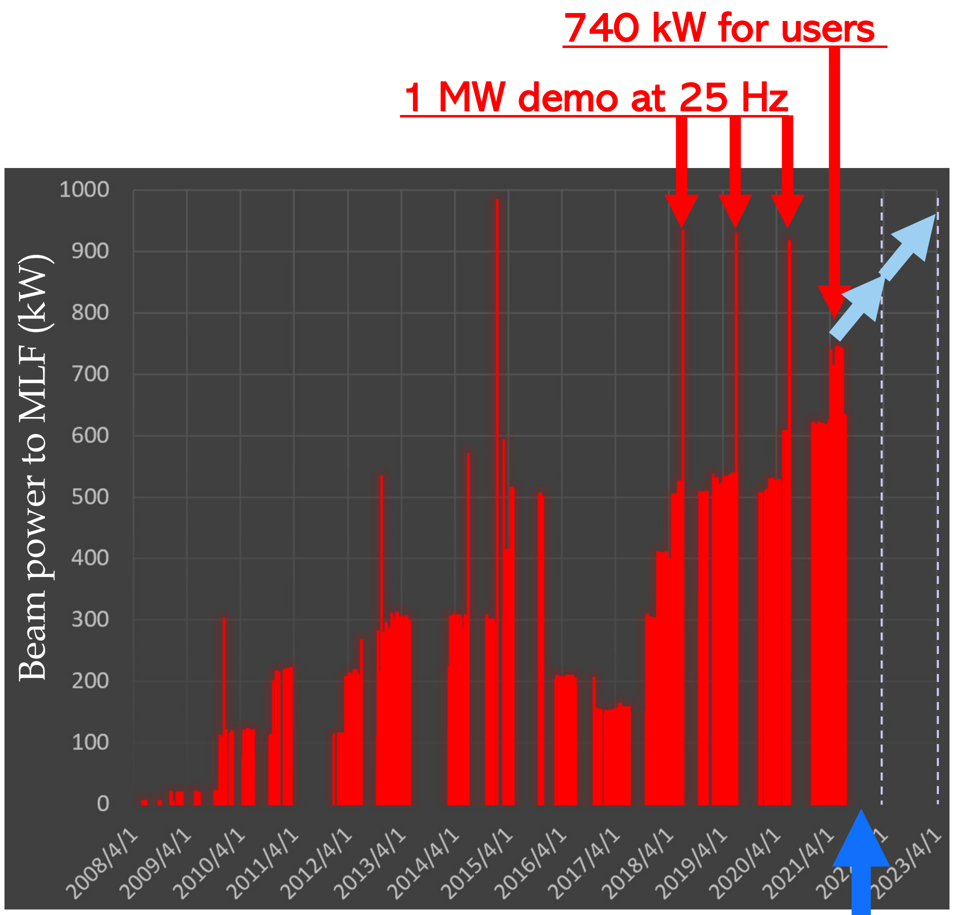



The RCS has two functions:

- Proton driver for producing pulsed muons and neutrons at the MLF,
- Injector to the MR.

# History of the RCS beam power

- ✓ We have already well demonstrated the 1-MW beam operation.




We are now in the summer maintenance period.

- ✓ But the routine beam power for users is still limited to 740 kW.
- ✓ J-PARC is still in the course of gradually increasing the beam power to 1 MW while carefully monitoring the durability of the neutron production target.
- ✓ The accelerator itself is already capable of 1 MW beam operation.
- ✓ If there are no unexpected troubles with the target, the beam power will reach nearly 1 MW in two years.

## 2. Review of 1-MW beam tuning for beam loss mitigation

- The most important issues in realizing MW-class high-power beam operations are controlling and minimizing beam loss, which are essential for sustainable beam operation that allows hands-on maintenance.
  - Beam loss limit: <3% at the injection energy (Collimator capability: 4 kW)

- In high-power machines such as the RCS, there exist many factors causing beam loss.
  - Space charge, lattice imperfections, foil scattering . . . .
  - Besides, beam loss generally occurs through a complex mechanism involving several factors.

→ Review our approaches to beam loss issues that we faced in the course of the beam power ramp up

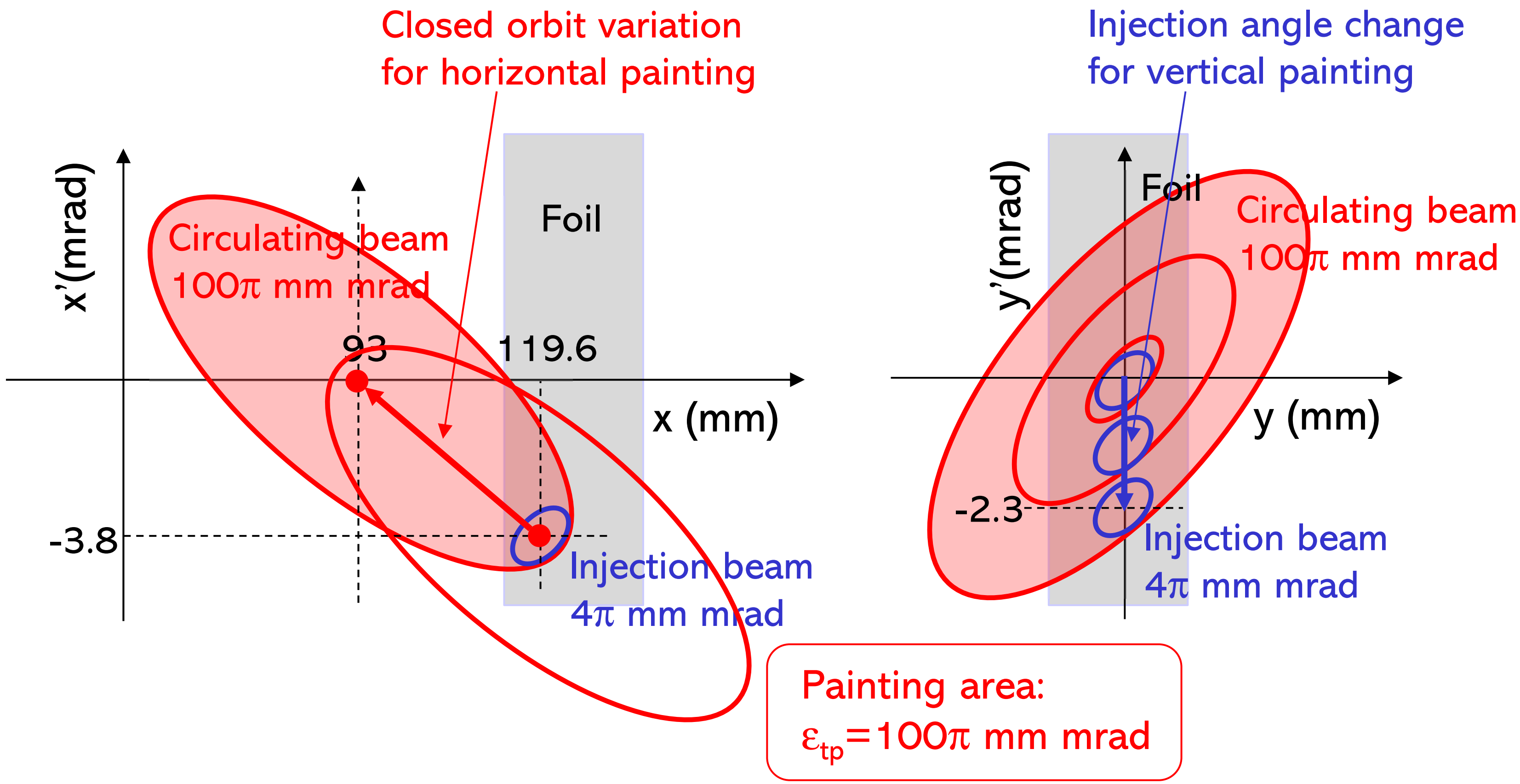
## 2.1 Beam loss reduction by injection painting

- ✓ In high-power proton synchrotrons,
  space charge in the low-energy region
  is one of the most crucial sources of beam loss.
- ✓ To mitigate this, RCS adopts
  transverse and longitudinal injection painting.

# Transverse injection painting

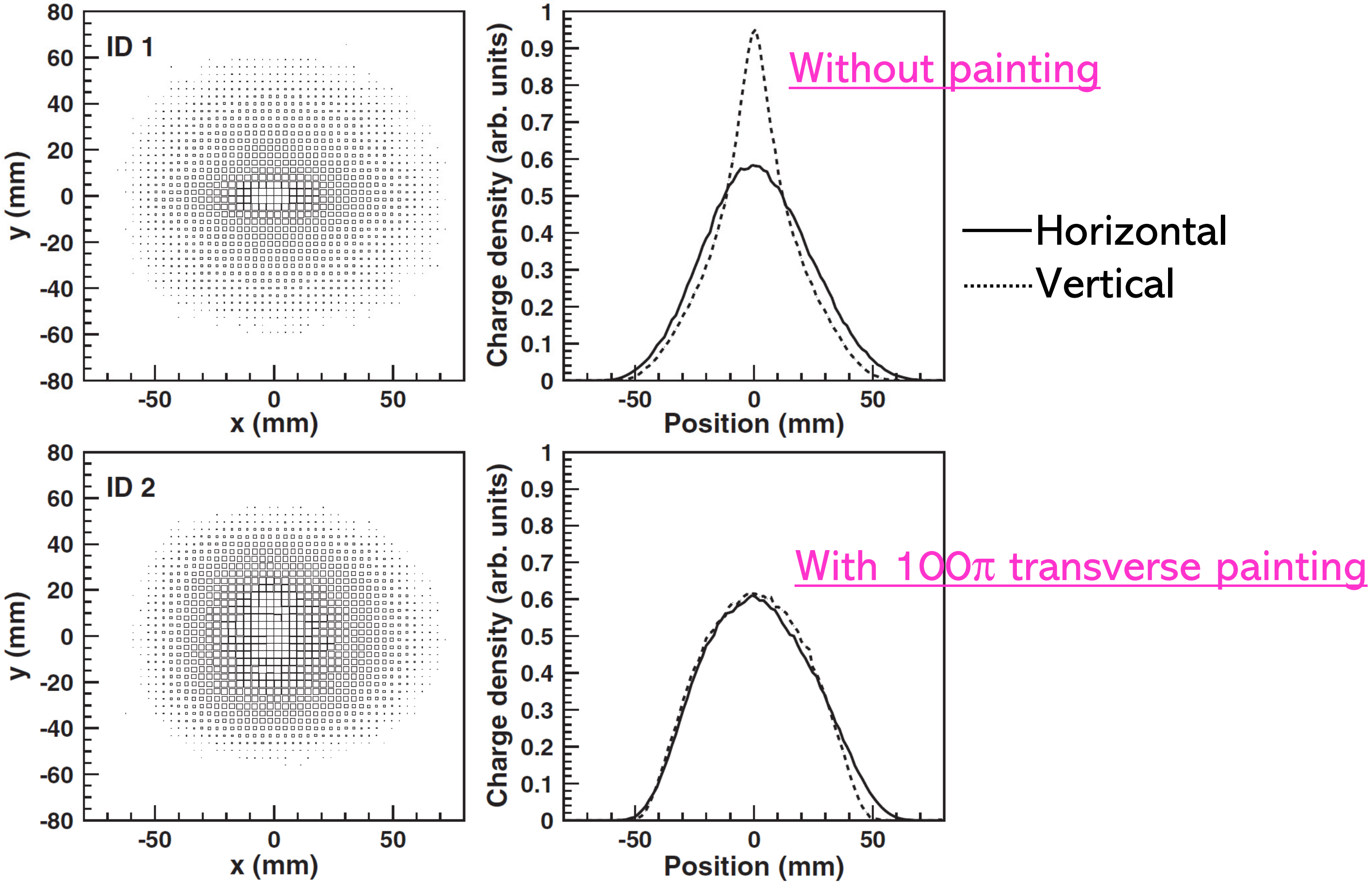
- ✓ In transverse painting, the phase space offset (Δx, Δx') & (Δy, Δy') between the centroid of the injection beam and the ring closed orbit is varied during multi-turn injection.
- ✓ By this way, the injection beam is uniformly distributed over a required painting area.

Schematic diagram of transverse injection painting



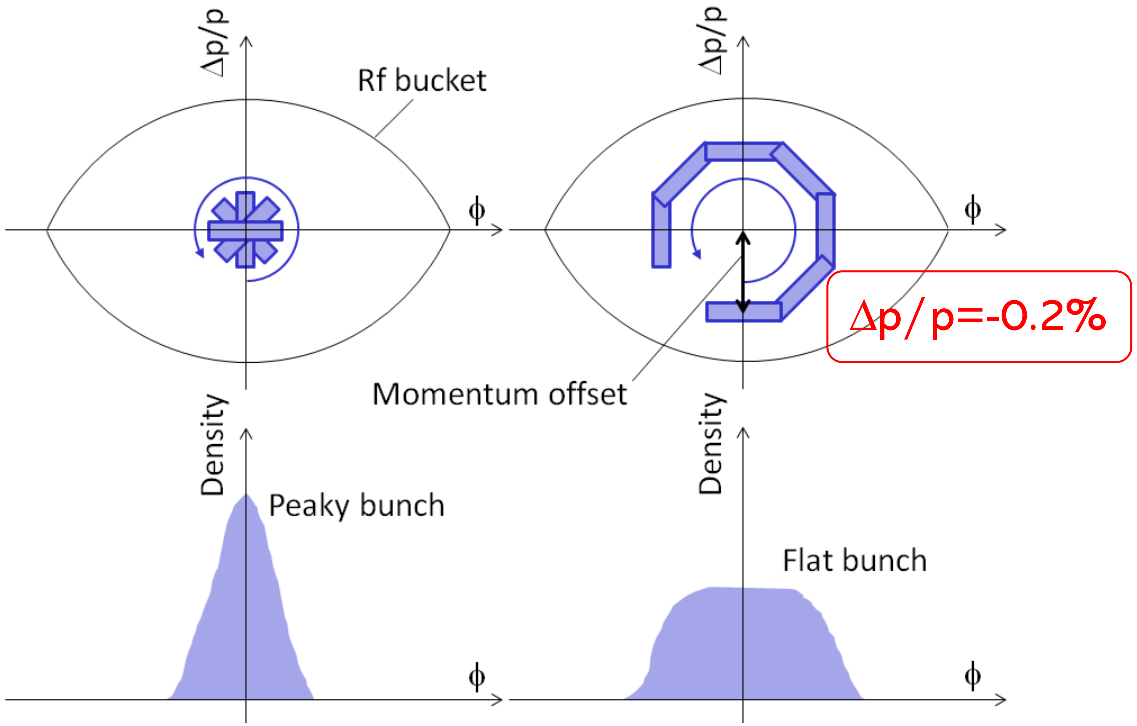
# Transverse injection painting

Transverse beam distributions at the end of injection
obtained without and with transverse injection painting




✓ Transverse injection painting well decreases the charge density peak in both the horizontal and vertical directions.

# Longitudinal injection painting



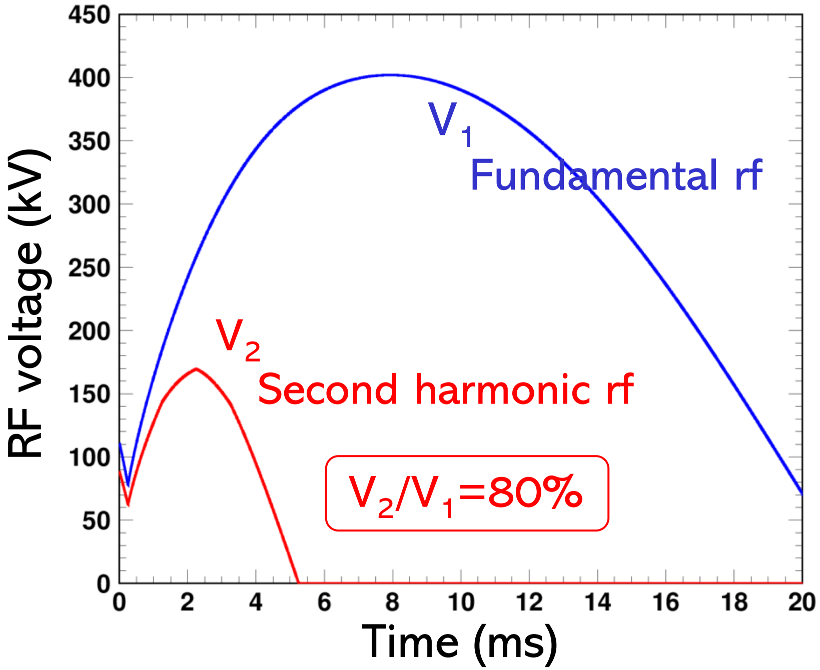

- ✓ In longitudinal painting,
  a momentum offset to the rf bucket is introduced during multi-turn injection.
- ✓ Uniform bunch distribution is formed through emittance dilution
  by a large synchrotron motion excited by the momentum offset.

# Longitudinal injection painting

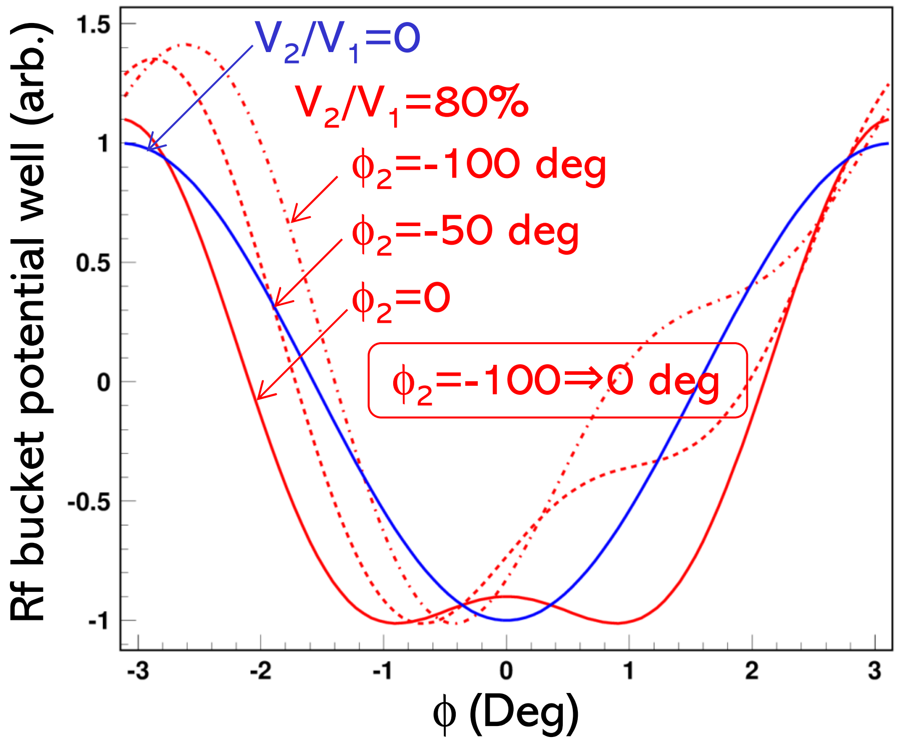
$V_{rf}=V_1\mathrm{sinf}-V_2\sin\{2(\phi-\phi_s)+\phi_2\}$

✓ In addition, for longitudinal injection painting, the second harmonic rf ($V_2$) and its phase sweep ($\phi_2$) are also introduced, which enable further bunch distribution control through a dynamical change of the rf bucket potential during injection.

Rf voltage pattern

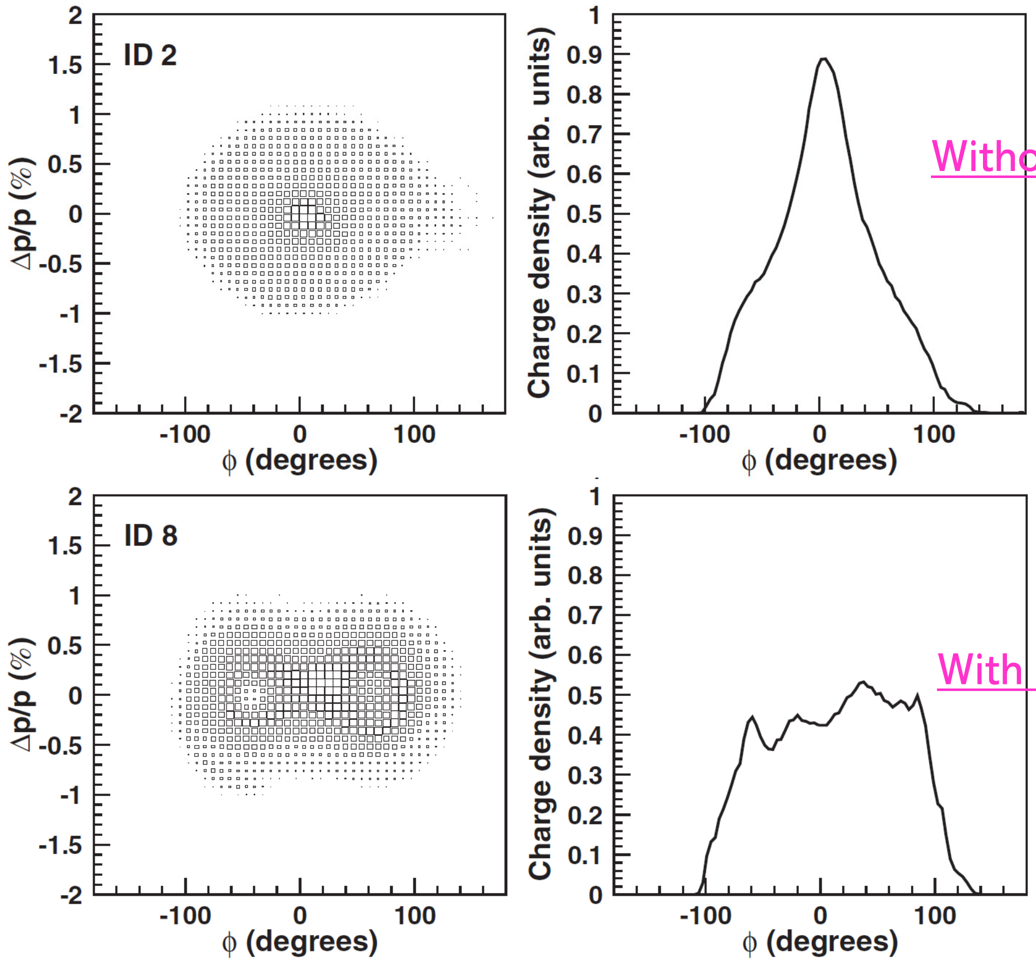



Variation of the rf bucket potential during injection



# Longitudinal injection painting

Longitudinal beam distributions at the end of injection
observed without and with longitudinal injection painting

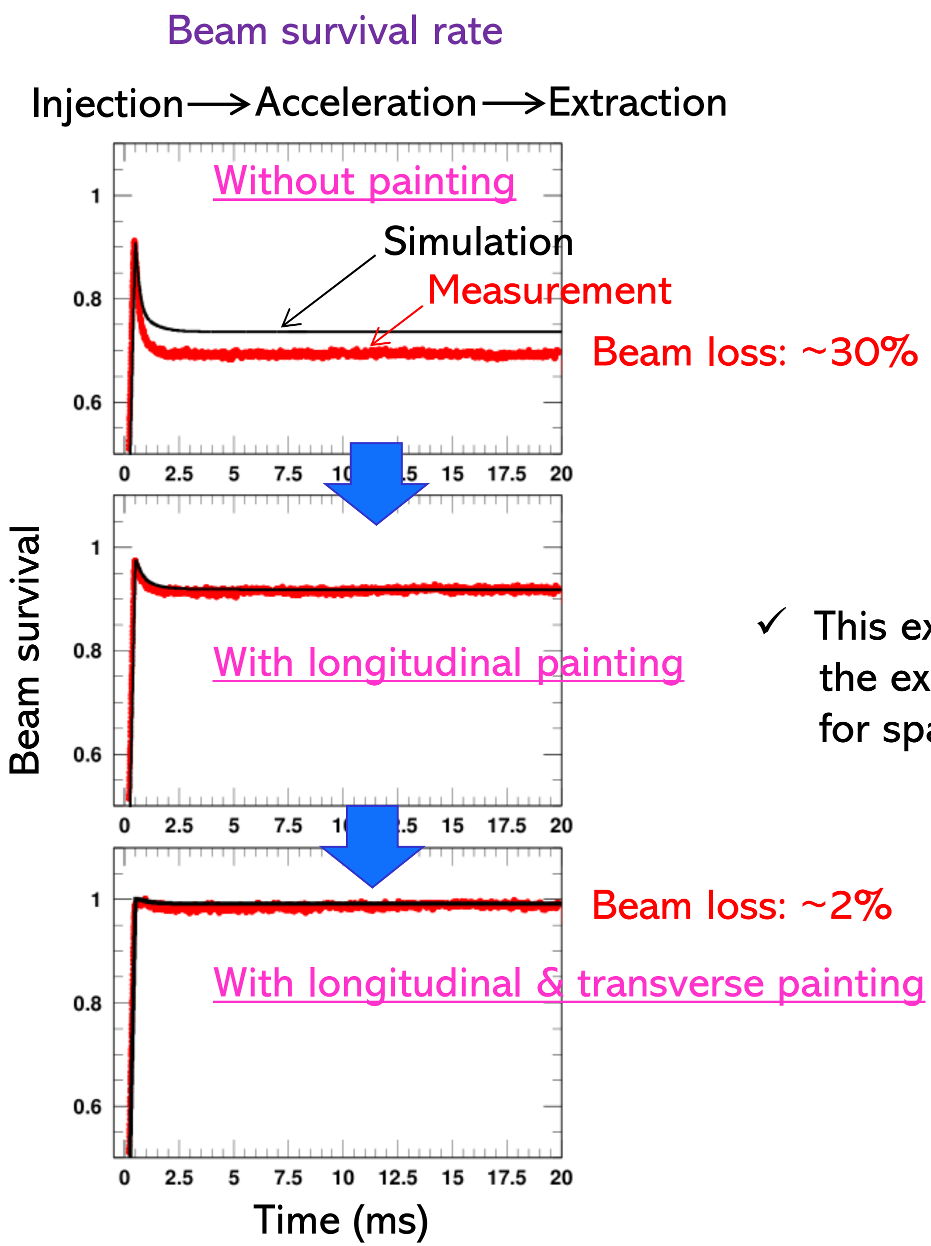



Without painting

With longitudinal painting

✓ By the longitudinal painting,
the charge density peak in the longitudinal direction is effectively reduced.

# Beam loss reduction achieved by injection painting

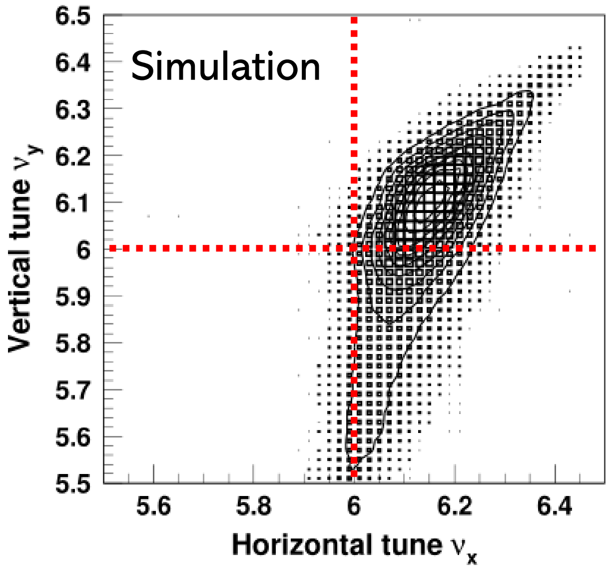



✓ This experiment clearly confirmed the excellent ability of injection painting for space-charge mitigation.

# Space charge mitigation achieved by injection painting

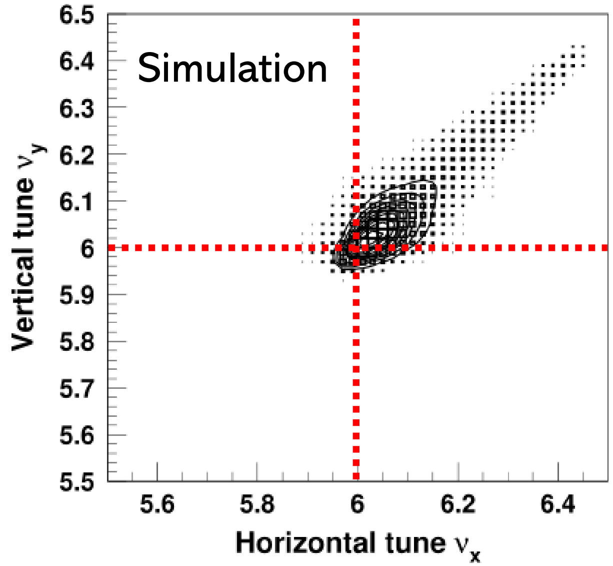
Tune footprints at the end of injection simulated without and with injection painting

Without painting




- ✓ A core part of the beam particles crosses the integers ($\nu$=6) due to large space-charge detuning.
- ✓ On the integers, all-order systematic resonances are excited (strong stopbands exist around the integers).
- ✓ The 30% large beam loss observed for the case with no painting is ascribed to the emittance growth caused by the stopbands.

With longitudinal & transverse painting

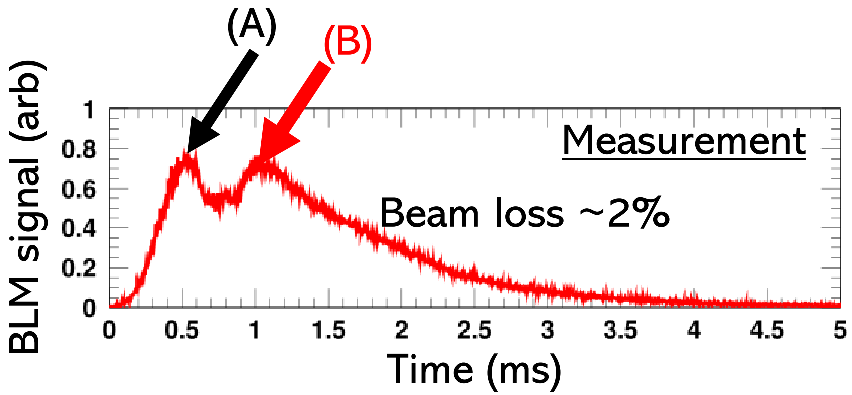



- ✓ Injection painting well decreases the space-charge detuning.
- ✓ This mitigates the effect of the stopbands, as a result, leading to the significant beam loss reduction.

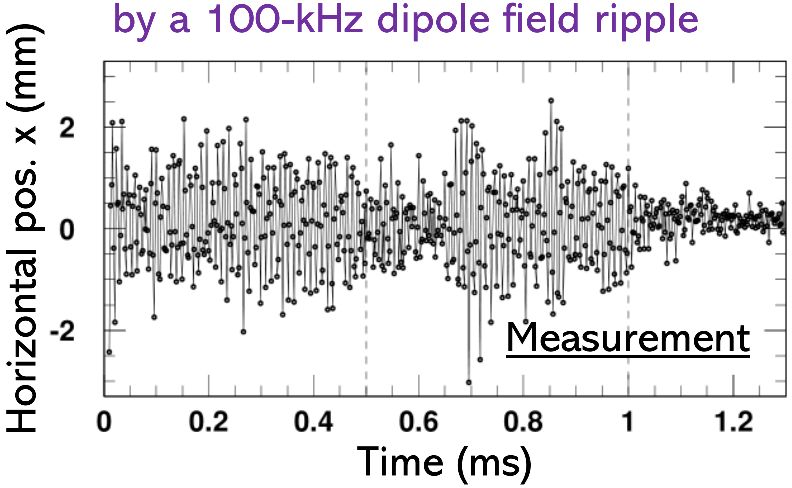
## 2.2 Approach to solving beam loss issue caused by the combined effect of space charge and dipole field ripple

# Beam loss caused by the combined effect of space charge and dipole field ripple

Time structure of beam loss measured after the introduction of injection painting




Beam position oscillation caused by a 100-kHz dipole field ripple




- ✓ By introducing injection painting, the beam loss was drastically reduced, but there still remained nonnegligible beam loss of ~2%.
- ✓ Further reduction of this beam loss was the next subject in our beam study.
- ✓ The beam loss consists of two peak structures.

  (A) : caused by scattering on the charge exchange foil during injection

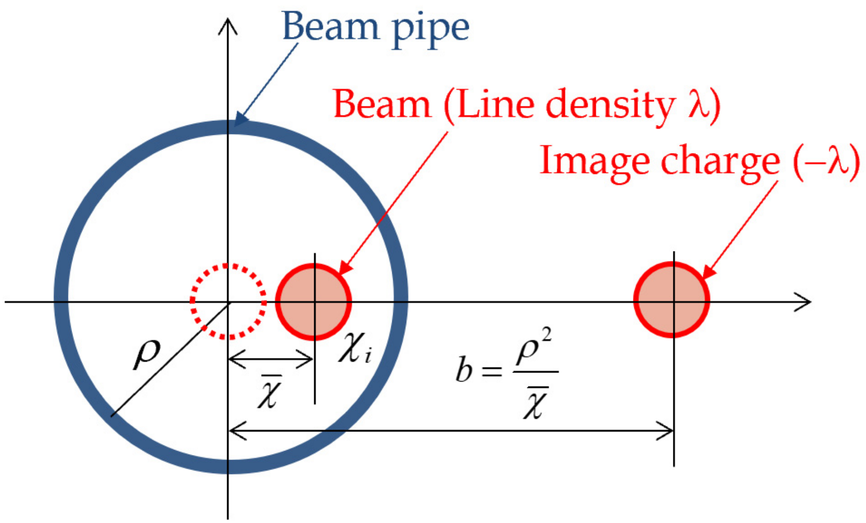
  . . . Very simple beam loss mechanism

  (B) : caused by a beam oscillation induced by a dipole field ripple.

  . . . Complex mechanism, which cannot be explained only by the presence of the beam oscillation.

  . . . For understanding the beam loss mechanism, we have to additionally consider the effect of the image charge of the beam.

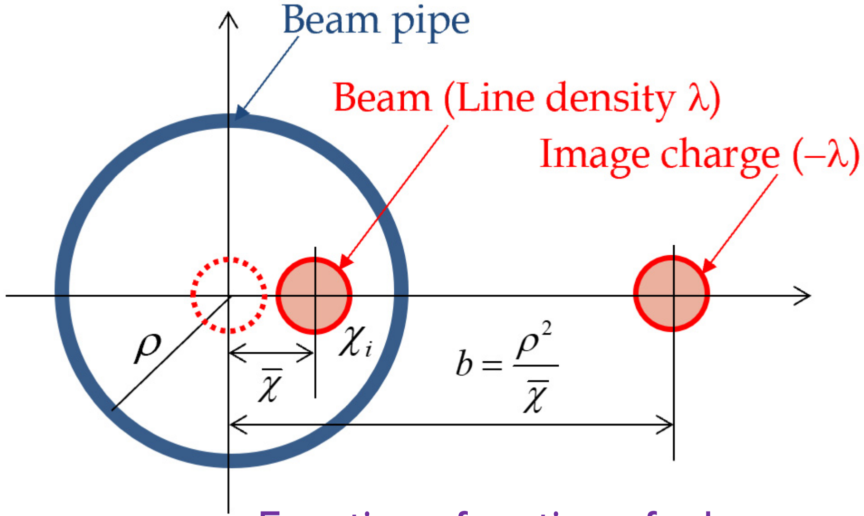
# Effect of image charge

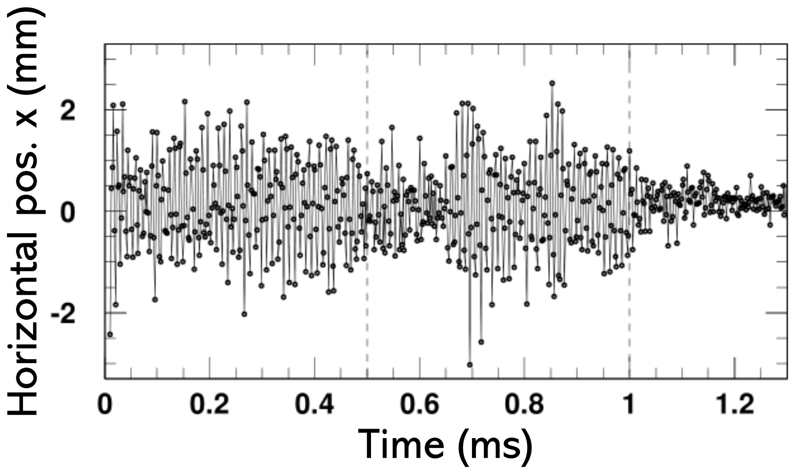



- ✓ Beam particles travel in the vacuum chambers, not in the free space.
- ✓ The image charge is an imaginary charge
  to provide the boundary condition of the beam pipe.

- ✓ The numerical simulation suggested that the second part of beam loss (B) is caused by the resonance driven by the combined effect of the beam oscillation and the image charge.

# Effect of image charge




Equation of motion of a beam particle in the center-of-mass system

Space charge

$$(\chi_i - \bar{\chi})'' + k(s)(\chi_i - \bar{\chi}) - \sum_j F_{sc\,ij} - \frac{2r_p\lambda\,\bar{\chi}^2}{e\beta^2\gamma\,\rho^4}(\chi_i - \bar{\chi}) \cdots = 0$$

External focusing fields

Direct space-charge among beam particles

Image charge

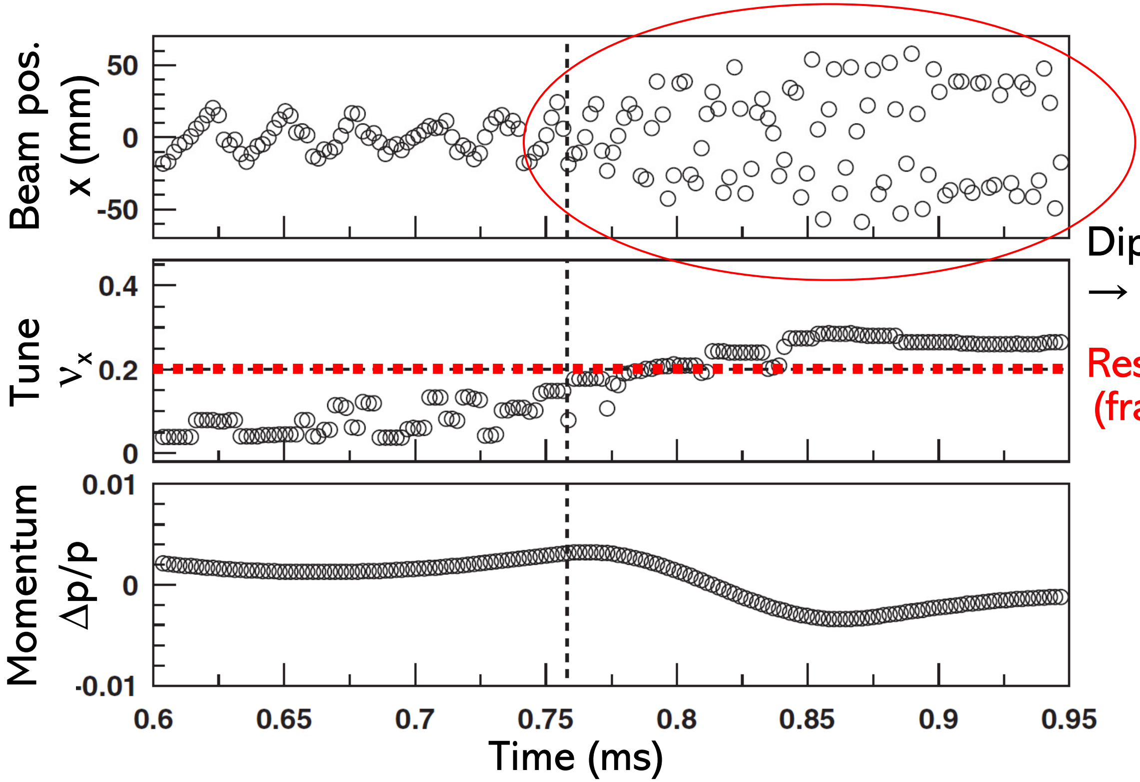
✓ The image charge has a simple defocusing effect on a beam particle, but the strength varies depending on the square of the beam position.

→ If the beam position oscillation is excited, the defocusing effect of the image charge periodically varies with 2 times higher frequency than that of the beam oscillation.

→ The oscillating defocusing force drives a second-order resonance at the corresponding betatron frequency (ν=0.2), affecting the beam.

# Resonance driven by the combined effect of space charge and dipole field ripple

Motion of a beam particle moving around the resonance

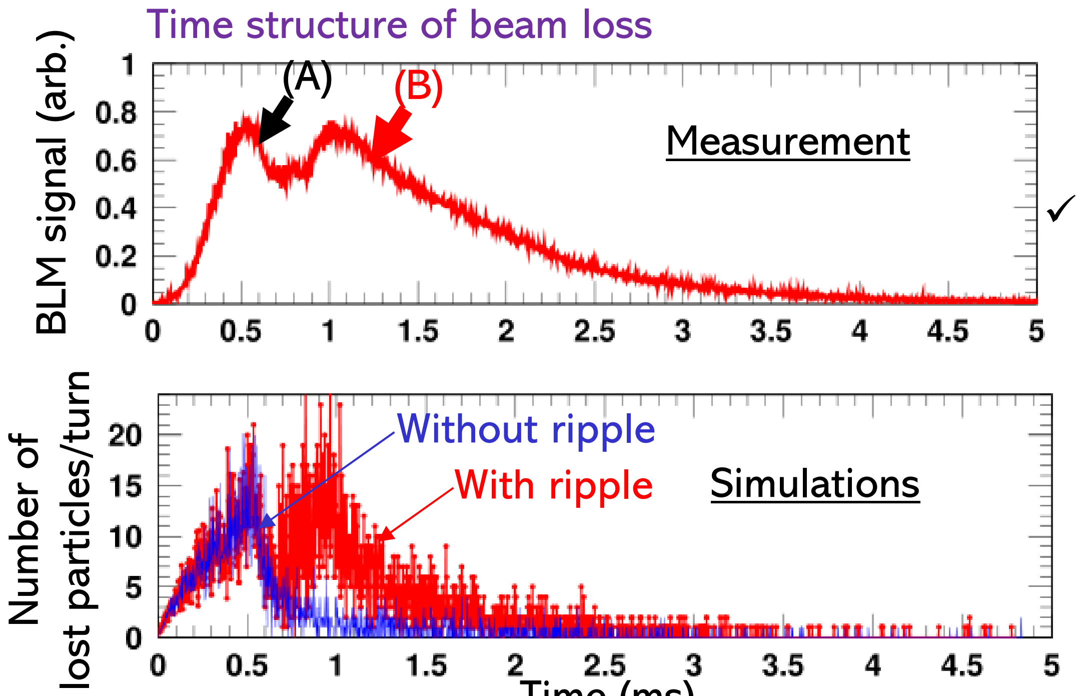



Dipole field ripple freq.: 100 kHz
→ Wavenumber per turn: 0.2

Resonant condition : $\nu$=0.2
(fractional part of the tune)

- ✓ The amplitude of the betatron motion of the beam particle sharply increases when the betatron tune gets on the resonance.
- ✓ The second part of beam loss (B) is ascribed to the beam halo formation caused by this resonance.

# Measurement vs. numerical simulation




- ✓ The experimental beam loss was well reproduced by the numerical simulation by including the measured dipole field ripple and by considering the realistic boundary condition.

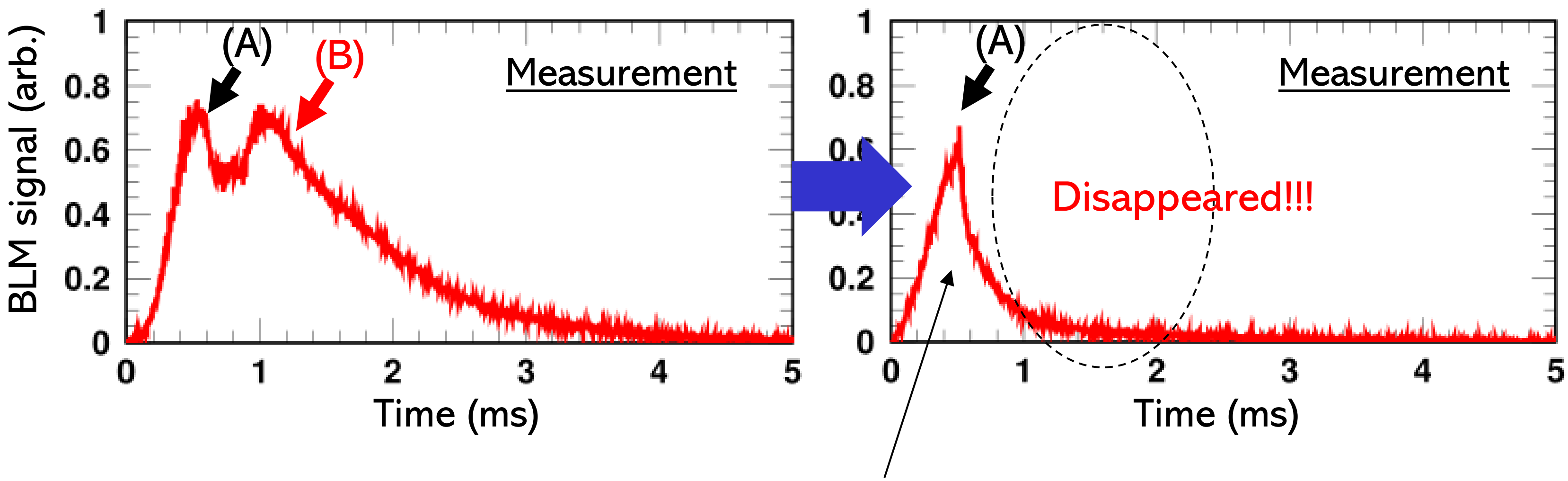
- ✓ The characteristic of the resonance is:
  - it is an intensity-dependent phenomenon.
  - it occurs at unusual betatron frequency depending on the frequency of the beam position oscillation.

- ✓ Through these numerical simulation studies, we revealed the complex mechanism of the beam loss.

## Measures against beam loss (B)

- ✓ Following the above beam study result, the power supply of the injection bump magnets, which was the source of the dipole field ripple, was improved.
- ✓ By this treatment, the dipole field ripple was drastically reduced, and as a result, the beam loss (B) was successfully removed.

Time structure of beam loss




(A): Foil scattering beam loss during charge-exchange injection

## 2.3 Approach to solving beam loss issue caused by the emittance exchange

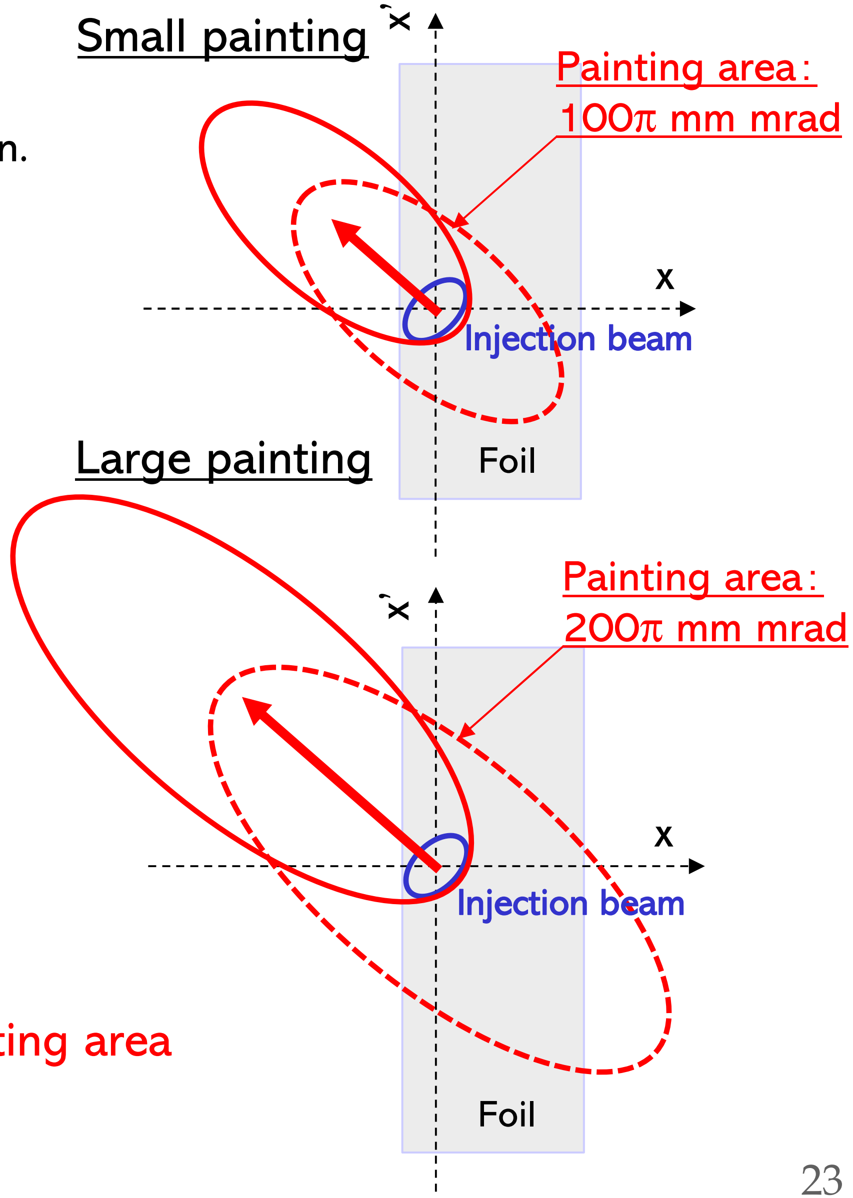
# Further reduction of the residual beam loss coming from foil scattering during charge-exchange injection

- ✓ The foil scattering beam loss occurs in proportion to the foil hitting rate during injection.

- ✓ One possible solution to reduce the foil hitting rate is to expand the transverse painting area.
  - The foil hitting rate can be reduced by larger painting, because the larger painting serves to more quickly move the circulating beam away from the foil.

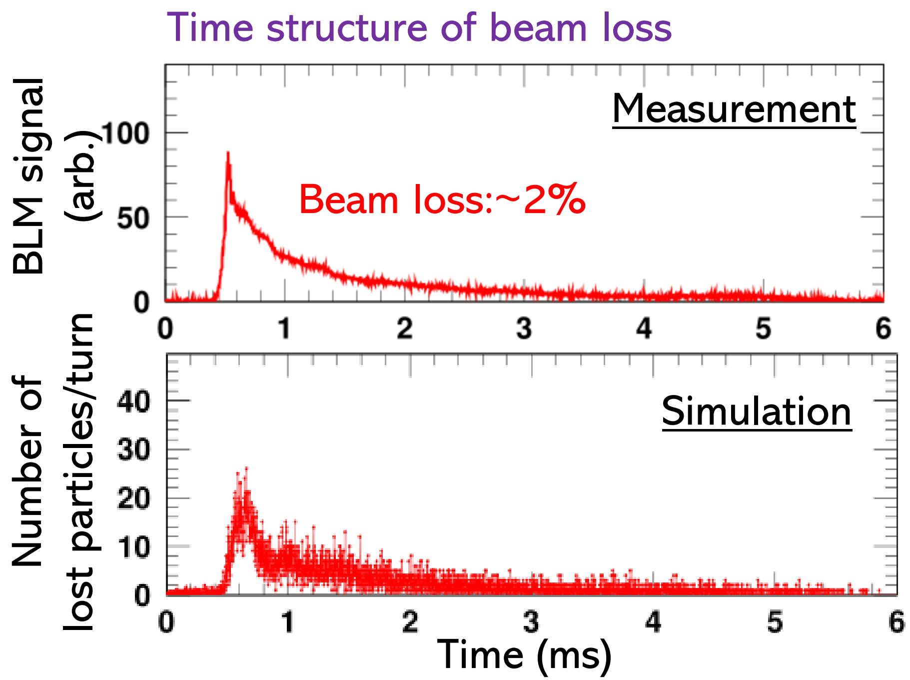
- ✓ The original painting area was 100π mm mrad.
  - The average number of foil hits per particle is as large as ~20.

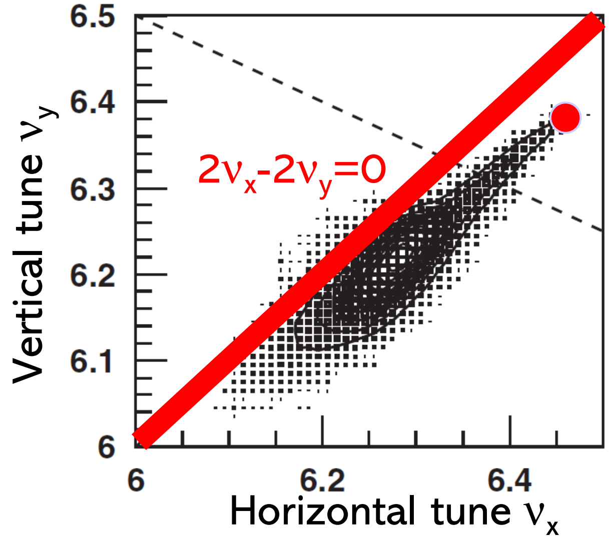
- ✓ This number can be reduced by ~1/4, if the painting emittance is doubly expanded.




But it was not so easy to expand the painting area from 100π to 200π mm mrad.

# Beam loss that additionally occurred for large painting

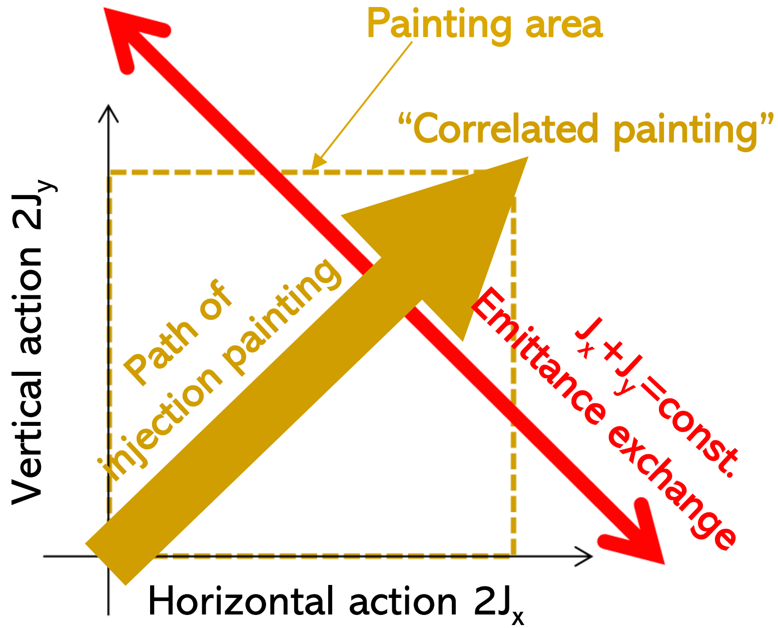



- ✓ By introducing large painting, the foil scattering beam loss was well reduced as expected, but another significant beam loss occurred.
- ✓ Also as to this beam loss, the numerical simulation gave a clue to solve this issue.
  - The numerical simulation well reproduced the experimental beam loss and clearly showed that the beam loss is caused by the nonlinear coupling resonance $2\nu_x-2\nu_y=0$.
  - This resonance is excited mainly by the nonlinear space-charge field, causing emittance exchange ($J_x$-$J_y$ exchange) between the horizontal and vertical planes.

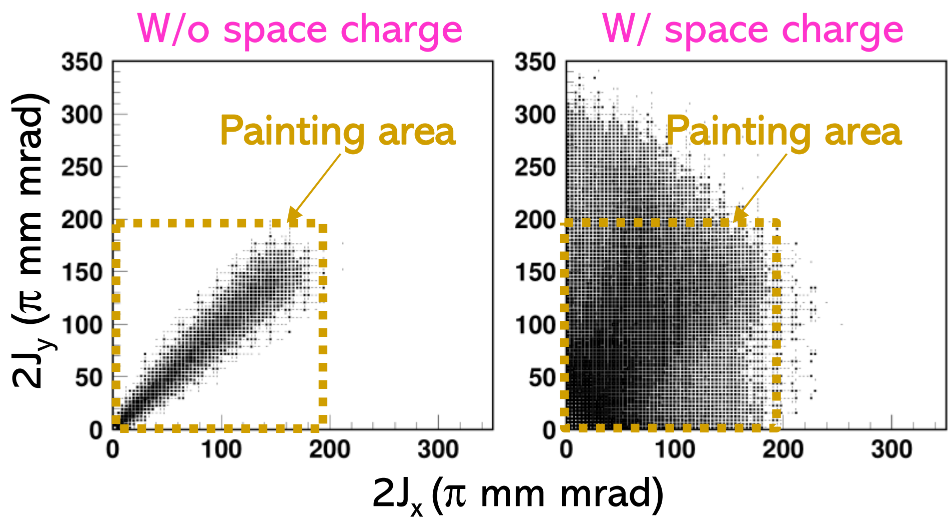
# Effect of emittance exchange on injection painting

2d space of the horizontal and vertical actions showing the mechanism of the beam loss




- The injection beam is painted from the middle to the outside on both the horizontal and vertical planes.
- To this direction of injection painting, the emittance exchange ($J_x$-$J_y$ exchange of particles) occurs in the orthogonal direction.

Scatter plots of the horizontal and vertical actions at the end of injection



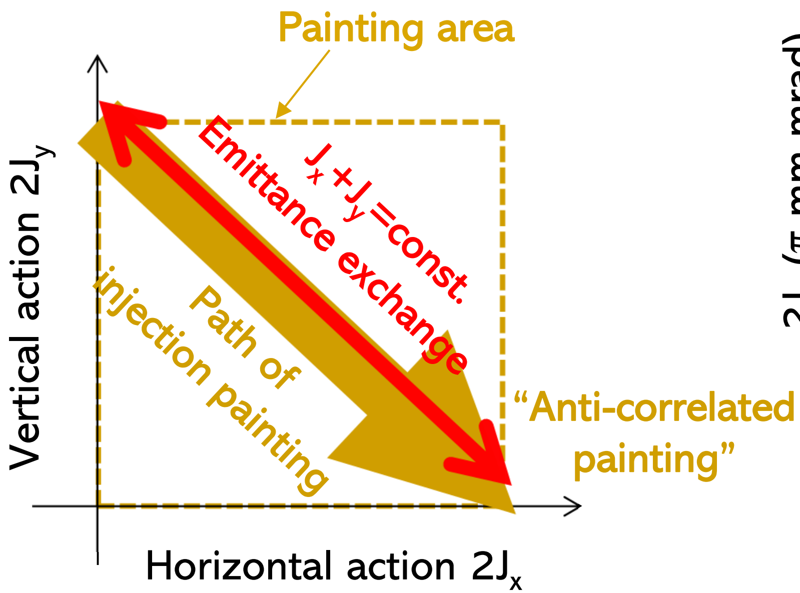

- The space charge makes a significant diffusion of beam particle away from the path of injection painting.
- The numerical simulation clearly showed that the diffusion of beam particles is caused by the emittance exchange that occurs perpendicularly to the path of injection painting.

・・・This is the mechanism of the beam loss.

# Measure against beam loss

✓ In order to solve the beam loss, we modified the path of injection painting.

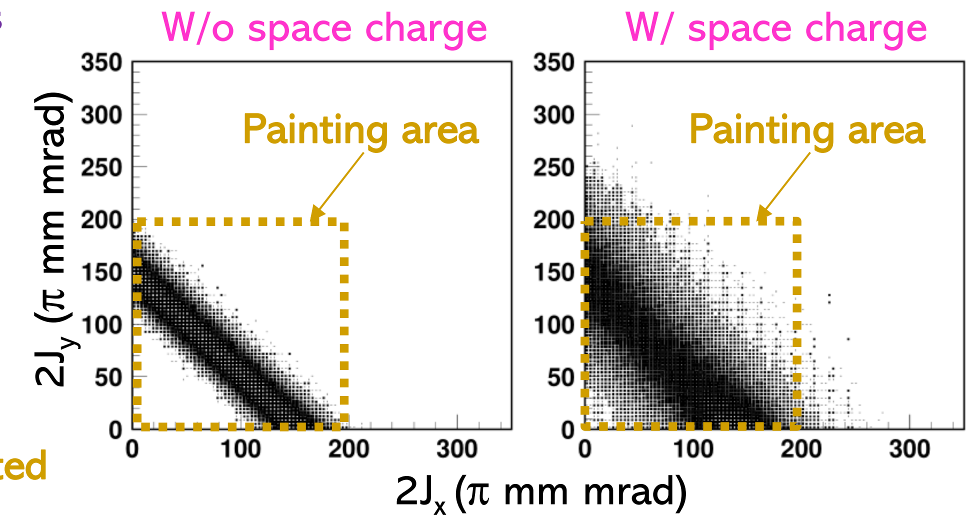
2d space of the horizontal and vertical actions




✓ The direction of vertical painting is reversed; the injection beam is painted from the middle to the outside on the horizontal plane, but from the outside to the middle on the vertical plane.

✓ The direction of the injection painting is the same as that of the emittance exchange.

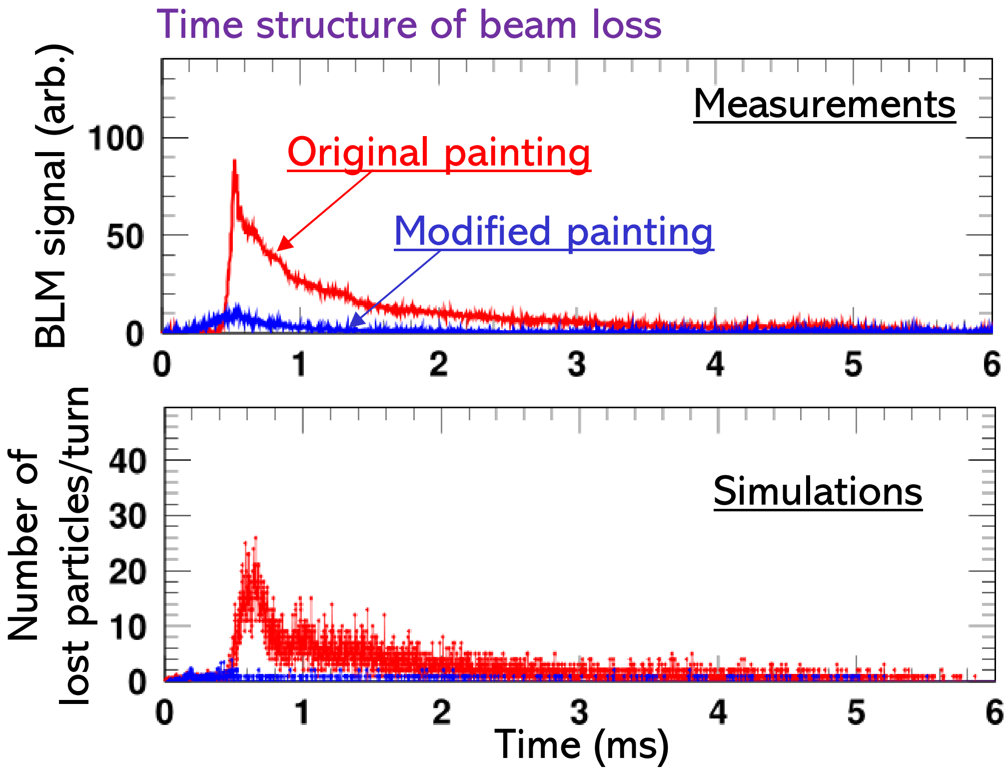
Scatter plots of the horizontal and vertical actions at the end of injection




✓ This geometrical relationship between injection painting and emittance exchange has an advantage, which minimizes the diffusion of beam particles.

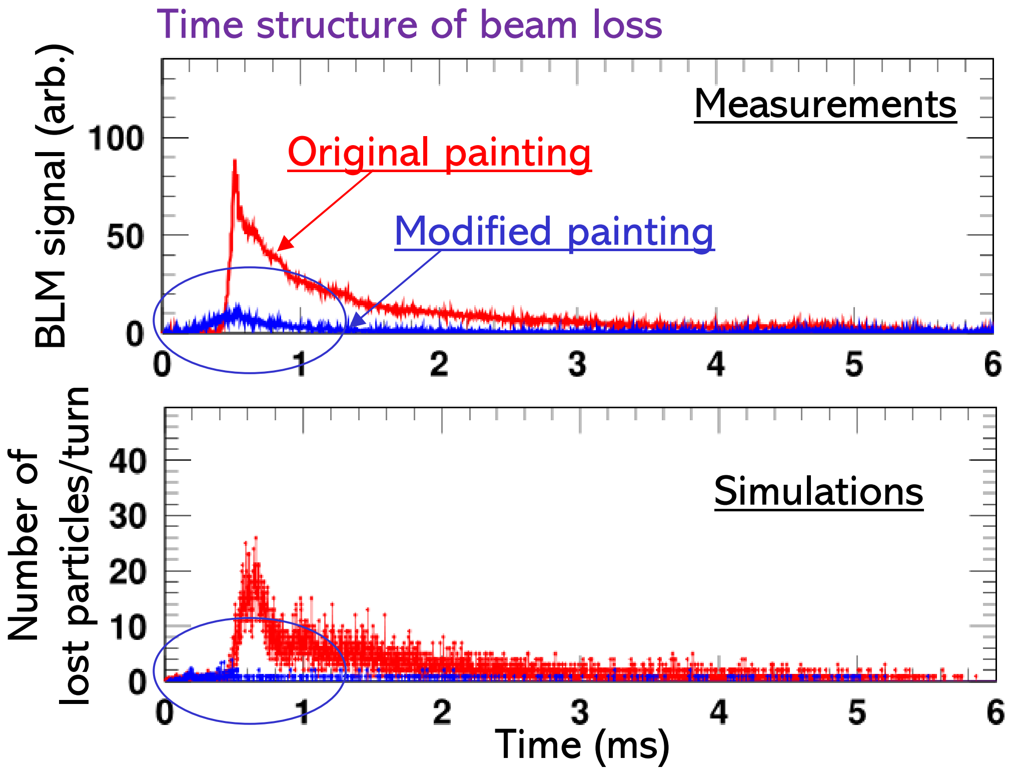
. . . Most of beam particles stay in the painting area though emittance exchange occurs, because the directions of the injection painting and the emittance exchange are the same.

# Measurements vs. numerical simulations




- ✓ The beam loss was successfully reduced by changing the path of injection painting, as predicted by the numerical simulations.
- ✓ By this treatment, we successfully doubly expanded the painting area with no significant additional beam loss.
- ✓ By this success of beam tuning, the foil scattering beam loss was sufficiently reduced.

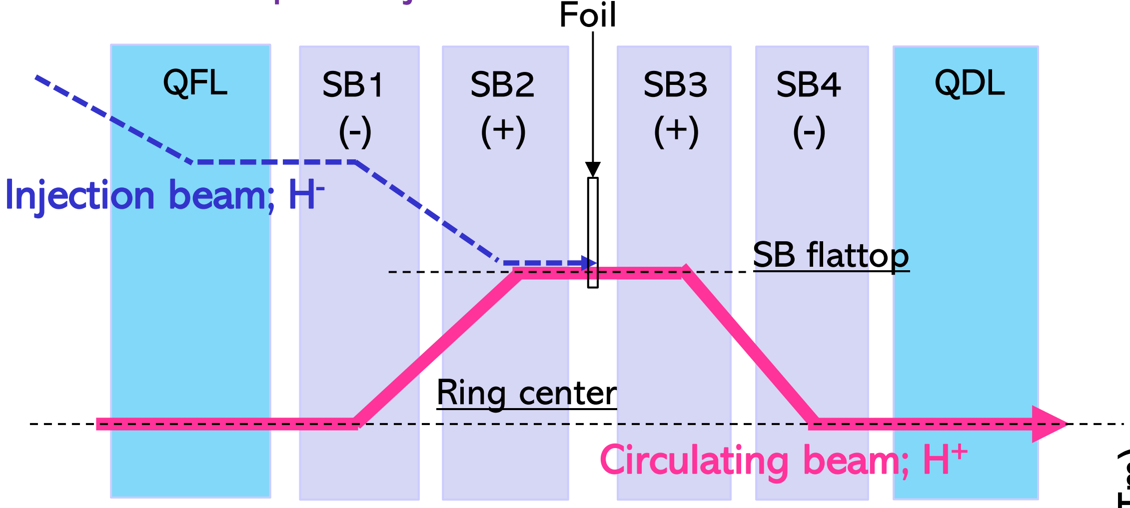
## 2.4 Source of residual beam loss



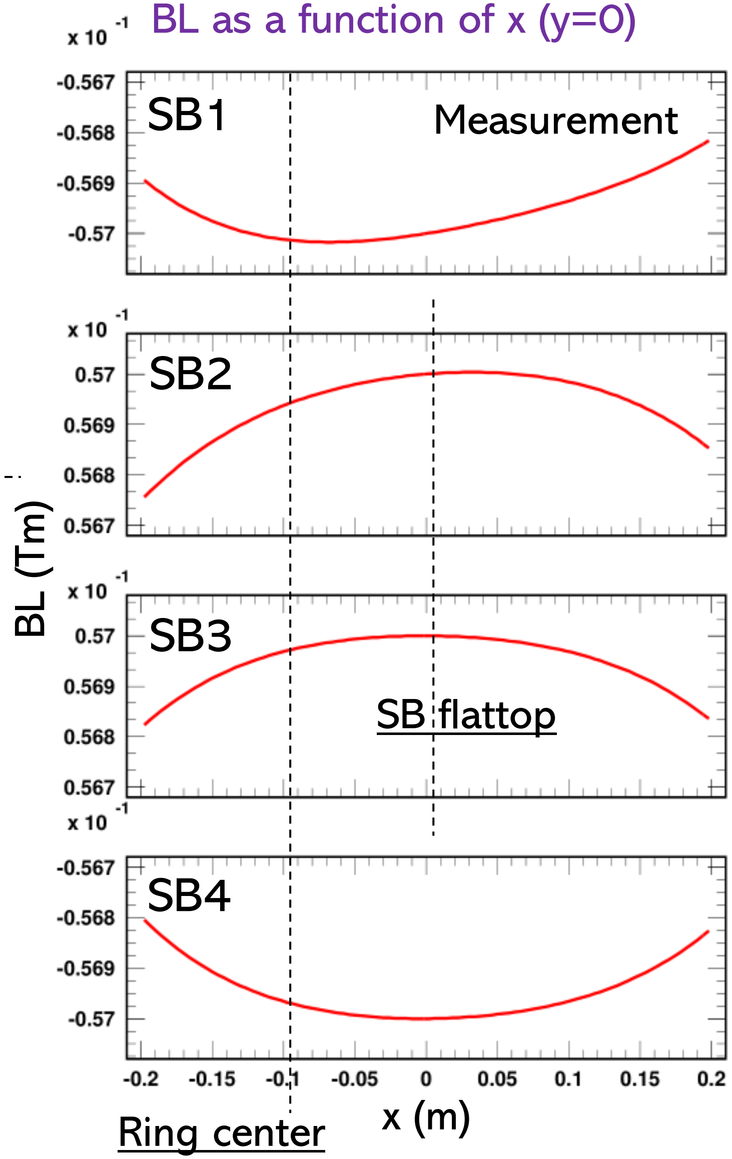

- ✓ By the continuous efforts, the beam loss in the 1 MW beam operation was finally reduced to the order of $10^{-3}$.
- ✓ The numerical simulation well reproduced the experimental beam loss, and found the residual beam loss arises from the effect of $3\nu_x=19$ driven by the sextupole field components intrinsic in the injection bump magnets.

# SB fields

Orbit bump for injection




BL as a function of x (y=0)




- ✓ Four sets of same-type pulsed dipole magnets (SB1-4) are used for forming an injection orbit bump of $\Delta x$=93 mm.
  - ➢ 0.5 ms flattop for multi-turn (307 turns) injection
  - ➢ 0.35 ms fall time

- ✓ Each SB has a significant sextupole component.

# Magnetic interferences

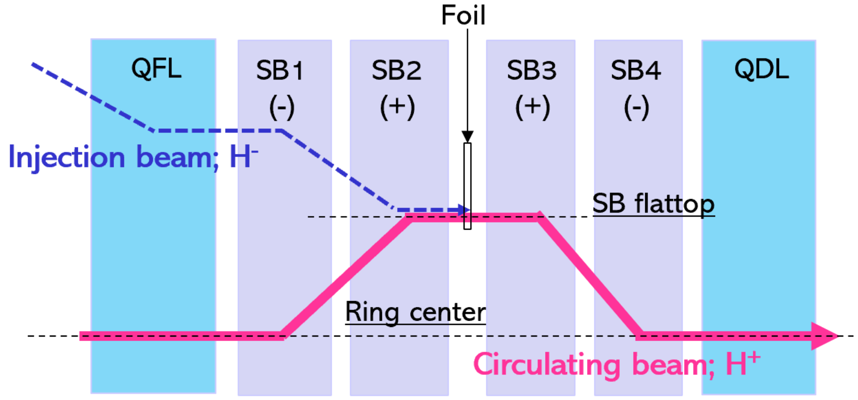
## IDEAL situation

✓ Ideally, the SB1-4 generate the same magnetic field distributions except polarity.

⇒ The SB fields including the high-order field components cancel with each other through the integration over the SB1-4.

⇒ The SB fields have no significant influence on the circulating beam.

**The actual situation is different from the above!**



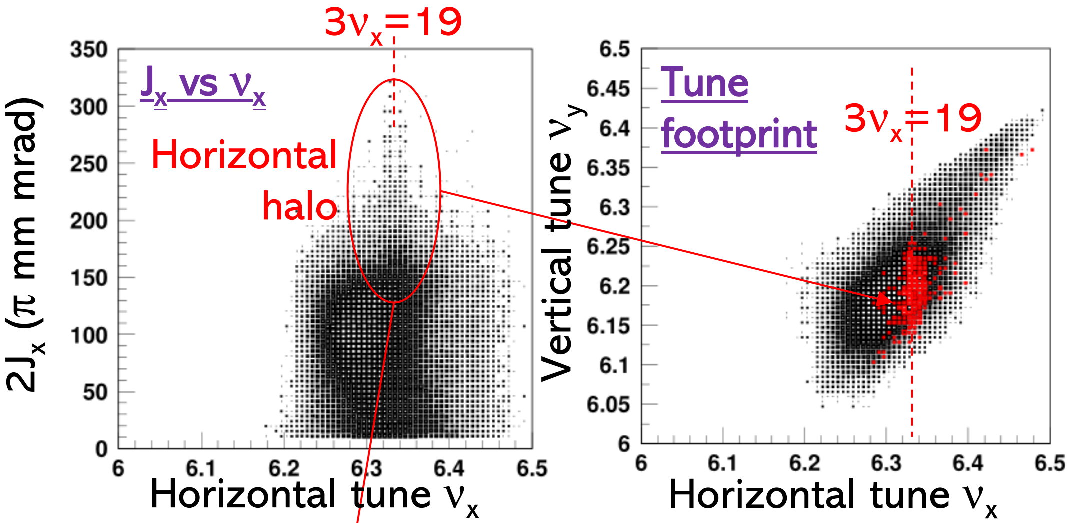

## ACTUAL situation

✓ Each SB has a different magnetic interference with each neighboring component.

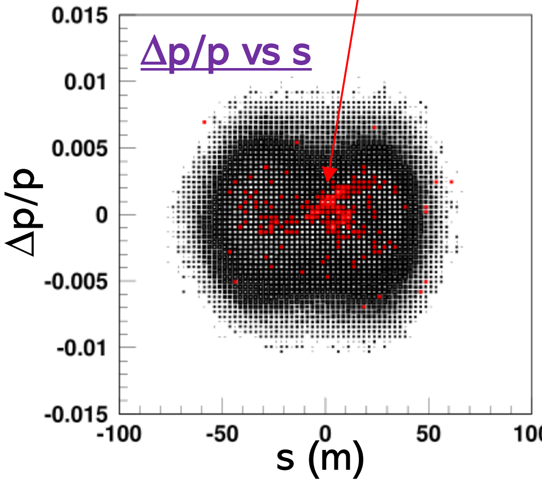
- The actual field distributions of the SB1-4 are not identical.
- In the actual beam operation, the SB fields are adjusted so that their dipole field components are compensated through the integration over the SB1-4.
- But, as to the higher-order field components, such a field compensation is incomplete due to the effects of the magnetic interferences.

✓ The residual sextupole component ($K_2$=0.012 $m^{-2}$), not cancels, excites $3\nu_x$=19, making a major part of the residual beam loss.

# Effect of the $3\nu_x$=19 resonance




calculated at the end of injection (t~0.5 ms)




- ✓ Most of the beam halo particles move around the middle of the longitudinal phase space.
- ✓ The tunes of such particles do not change widely turn by turn.
  - The $\Delta p/p$ of such particles do not change widely.
    → The turn-by-turn change of the chromatic tune shift is restrictive.
  - The effect of space charge on such particles are almost constant due to the flat bunch distribution.
    → The turn-by-turn change of the space-charge tune shift is also restrictive.
- ✓ A part of such inactive particles stays near $3\nu_x$=19 for a relatively long time and continuously suffers the effect of the resonance.

  → Horizontal beam halo formation, making a major part of the residual beam loss.

## 2.5 Result of the optimization for the 1-MW beam operation

The amount of the residual beam loss is the order of $10^{-3}$;

- sufficiently small
- concentrated in the injection energy region,
- well localized at the collimator section.

→ We performed a ~2-day continuous 1 MW beam operation for users right before the summer maintenance period in 2020.

- No serious troubles
- No unexpected increase in the residual radiation levels

  Injection area <80 μSv/h
  Collimation area <350 μSv/h
  High dispersion area <3 μSv/h
  . . . measured at 30 cm, 5 hours after the beam stop

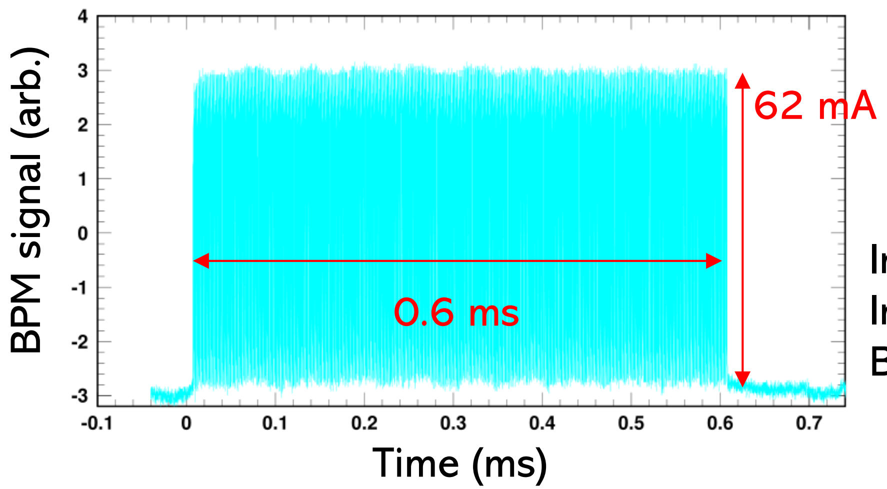
→ Now we can say the accelerator itself including the linac is ready for the 1 MW beam operation.

→ The successful achievement of the low-loss 1 MW beam operation opened the door to further beam power ramp-up beyond 1 MW.

# 3. Recent efforts toward further beam power ramp-up beyond 1 MW

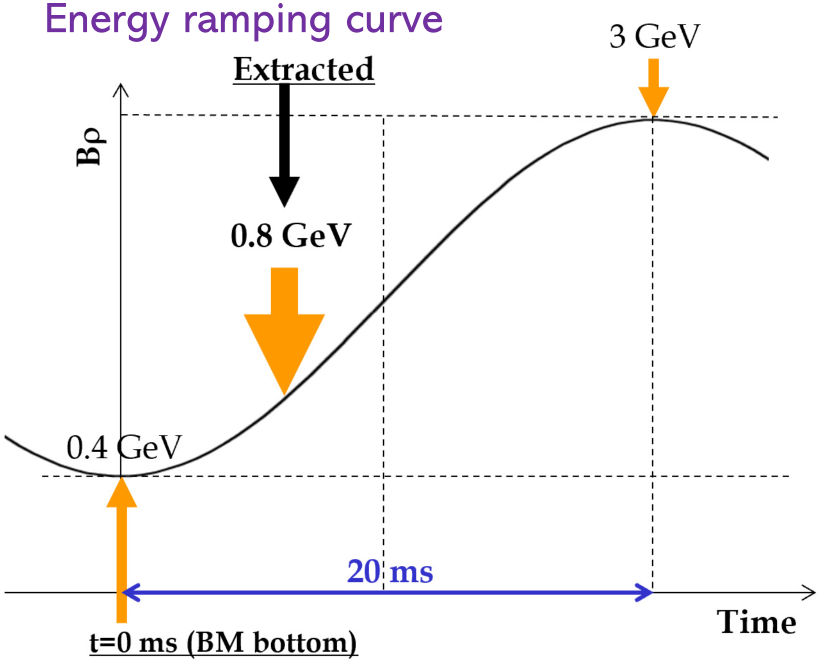
# High-intensity beam test towards >1 MW

Linac beam pulse




| | 1 MW | | 1.5 MW |
|---|---|---|---|
| Injection peak current: | 50 mA | ⇒ | >60 mA |
| Injection pulse length: | 0.5 ms | ⇒ | 0.6 ms |
| Beam intensity: | 8.33e13 | ⇒ | 1.26e14 |

Energy ramping curve

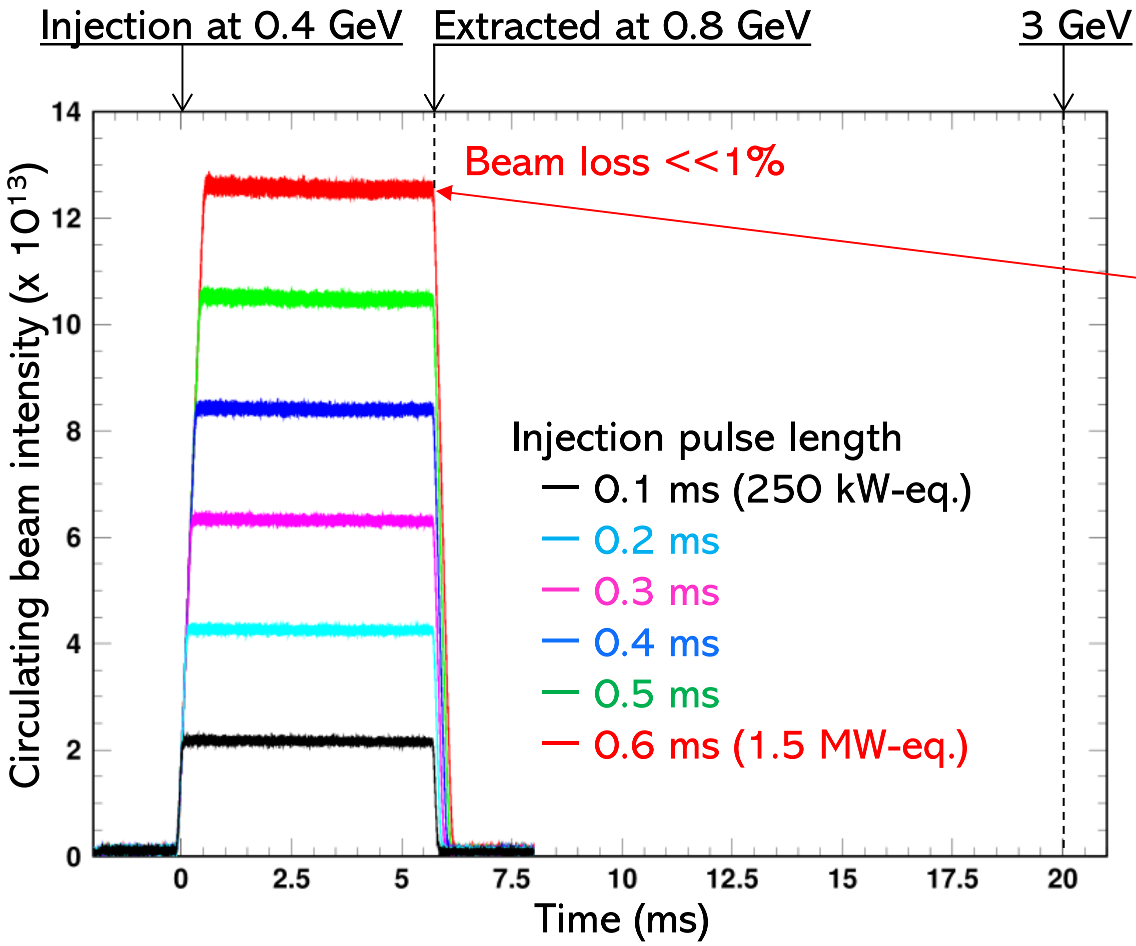



Due to the limitation of the ring RF system,
the full acceleration of up to 3 GeV was not reached,
but we achieved the 0.8 GeV acceleration.

Beam loss usually occurs
for low energy region below 0.8 GeV.

So, we were able to complete
sufficient beam loss study even for the situation.

# Experimental result




Beam intensity:

**$1.26 \times 10^{14}$ ppp**

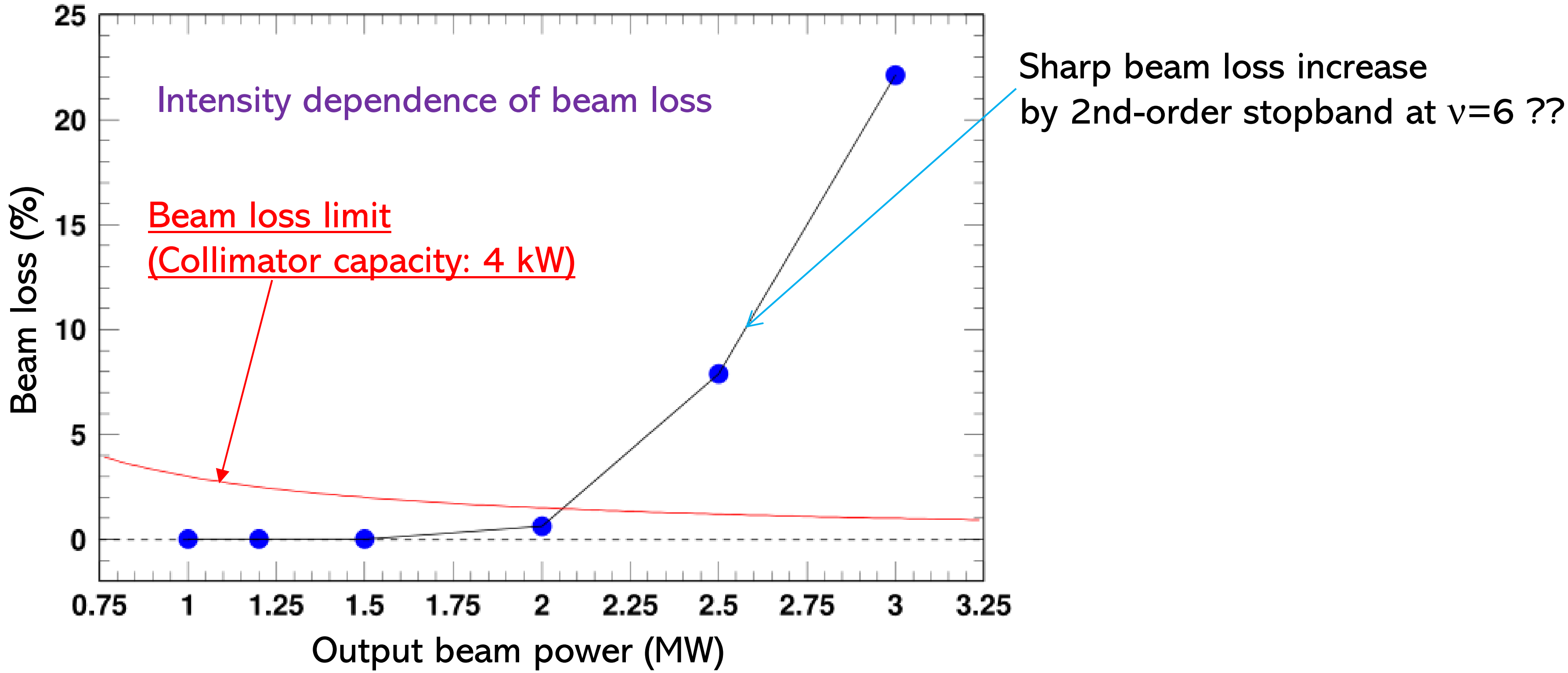
corresponding to **1.5 MW**

if running at 3 GeV and 25 Hz.

- ✓ The beam loss at low energy, which was the most concern, was successfully reduced to the order of $10^{-3}$ even for the 1.5 MW-eq high-intensity beam.

- ✓ To realize actual 1.5 MW beam operation, we need several hardware upgrades, such as the upgrade of the ring RF system.
- ✓ But this experimental result clearly shows the J-PARC RCS has a sufficient potential to realize such a high-power beam operation beyond 1 MW.

# 1~3 MW simulations




- ✓ This numerical simulation suggests the possibility of low-loss 2 MW beam operation.
- ✓ We are now promoting high-intensity beam tests toward further beam power ramp-up beyond 1 MW, looking ahead to future upgrades of J-PARC, such as the construction of the second target station.

## 4. Summary

- ✓ J-PARC is now in the course of gradually increasing the beam power to 1 MW while carefully monitoring the durability of the neutron production target.
- ✓ But the accelerator itself is ready for the 1 MW beam operation.
- ✓ By continuous efforts for beam loss mitigation including hardware improvements, we have recently established a 1-MW beam operation with considerably low fractional beam loss of a couple of $10^{-3}$.
- ✓ This beam loss amount corresponds to <1/10 the typical value in the previous high-intensity proton synchrotrons.
- ✓ This success of the low-loss 1-MW beam operation opened the door to further beam power ramp-up beyond 1 MW.
- ✓ Looking ahead to future upgrades of J-PARC, we are now promoting further high-intensity beam tests toward achieving a 1.5-MW beam power or more.

Thank you very much.