Beam loss issues in the high-intensity beam operation at J-PARC RCS

Space charge 2019

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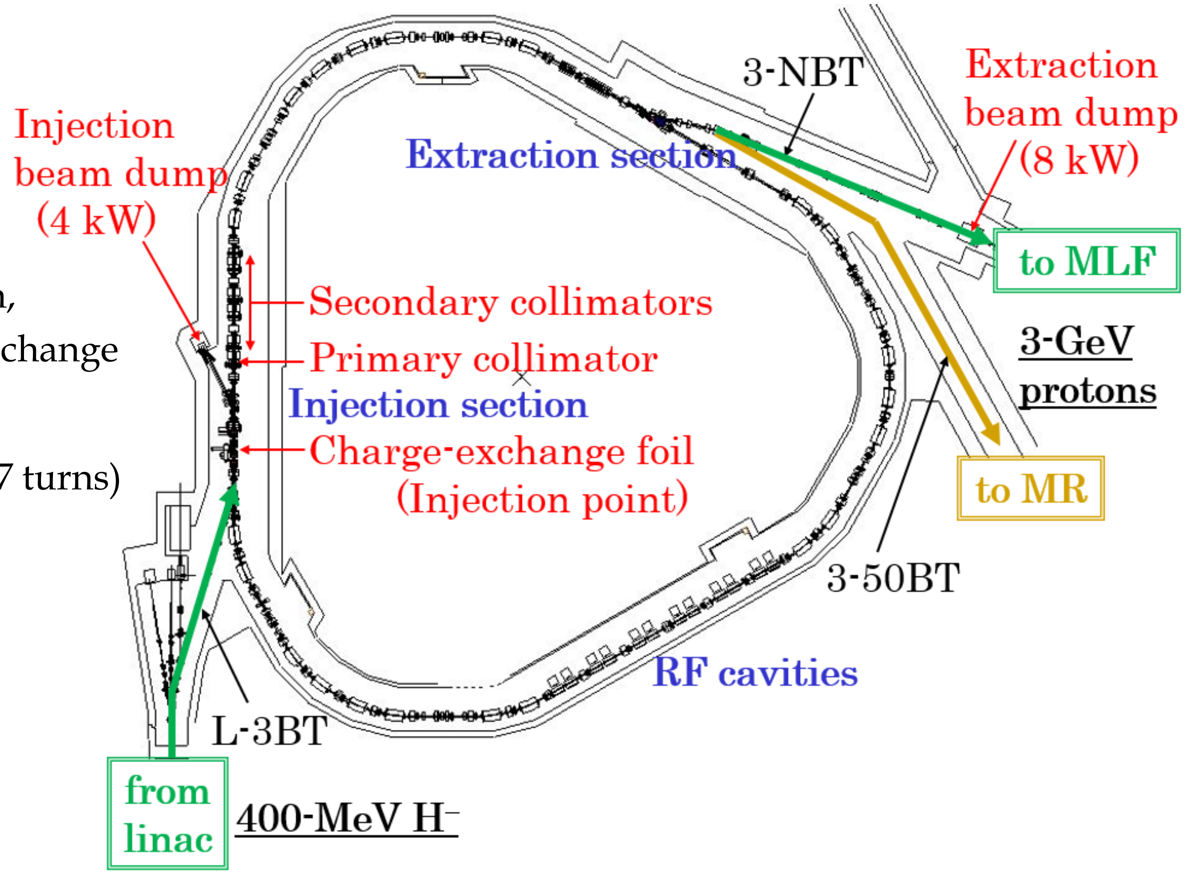
Contents of my talk

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	8.33×10^{13}
Beam power	**1 MW**

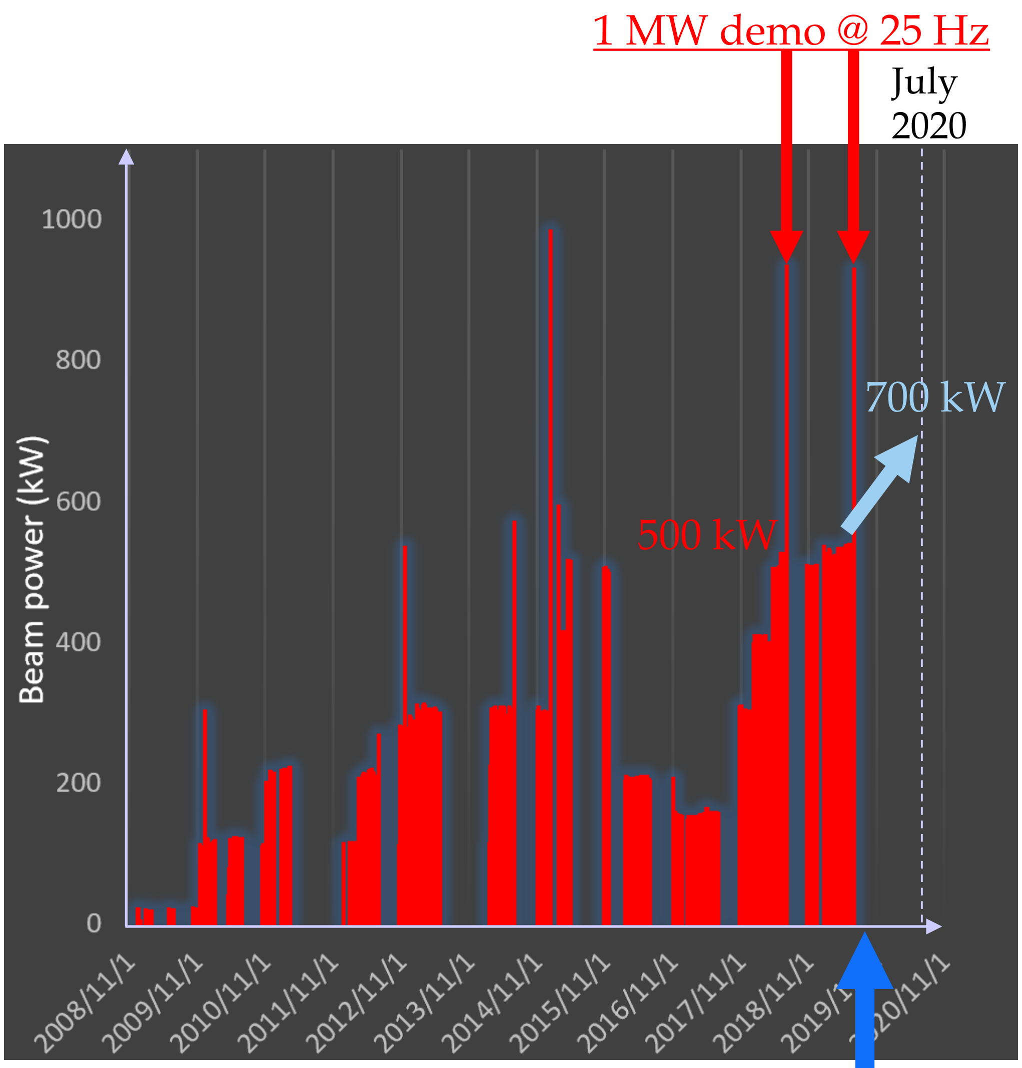


The RCS has two functions;

- **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 design beam operation.**



We are now in the summer maintenance period!

✓ The routine beam power is still limited to 500 kW due to a delay of the development of the MLF target tolerant of the 1-MW beam power.

✓ For the past two years, the effect of the beam on the damage to the target was carefully investigated with the 500-kW beam.

✓ We will install a new robust target in this summer maintenance period, then gradually ramping up the beam power, first, up to 700 kW by the next summer.

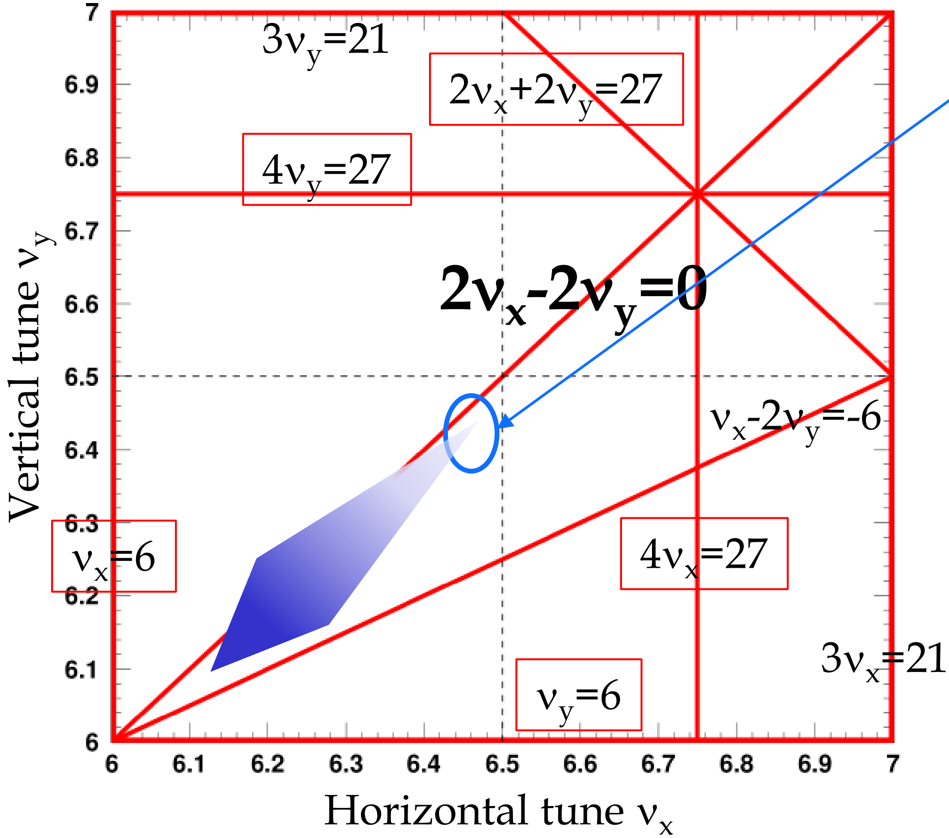
✓ The beam power ramp-up after the next summer will be determined considering the situation of the target at the stage.

✓ It takes 1~2 years to realize the 1-MW routine user operation depending on the situation of the target development.

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

Tune diagram near the operating point

— Systematic resonances up to 4th order derived from the 3-fold symmetric lattice of the RCS

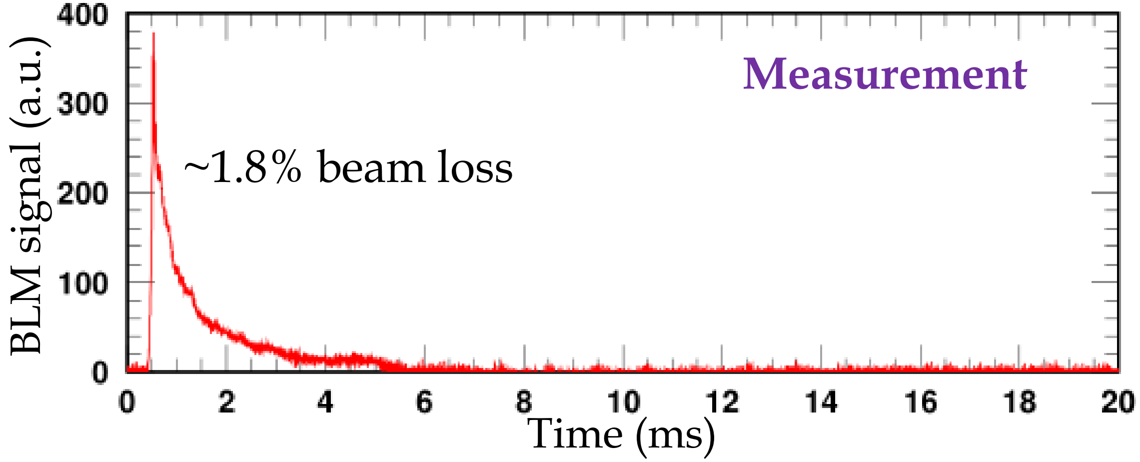


Initial operating point

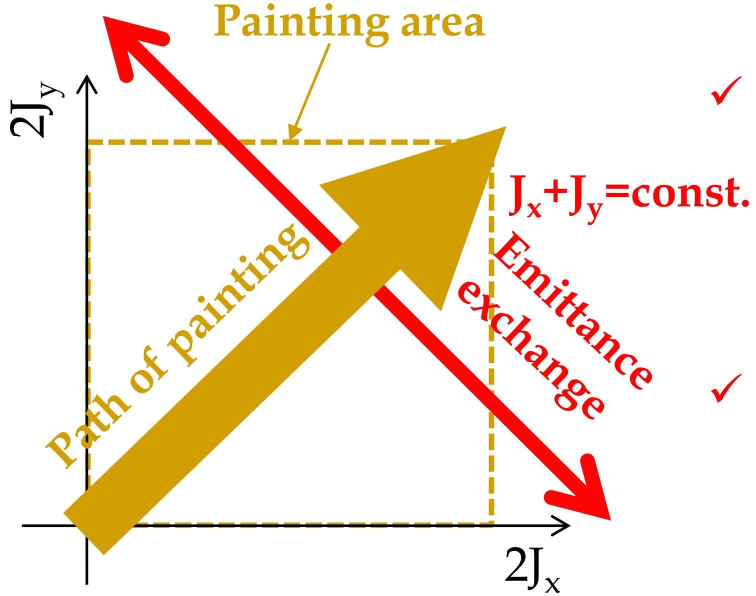
- ✓ The operating point allows tune shifts to avoid serious resonances, $\nu_{x,y}$=6, $4\nu_{x,y}$=27, $2\nu_x+2\nu_y$=27, etc.
- ✓ It is very close to $2\nu_x-2\nu_y$=0.
- ✓ The $2\nu_x-2\nu_y$=0 resonance is not so serious, just causing emittance exchange. . . . We thought so first.
- ✓ But, the emittance exchange had a major influence on the formation of the beam distribution during injection painting and it caused significant beam loss.

Beam loss caused by Montague resonance

Time structure of beam loss



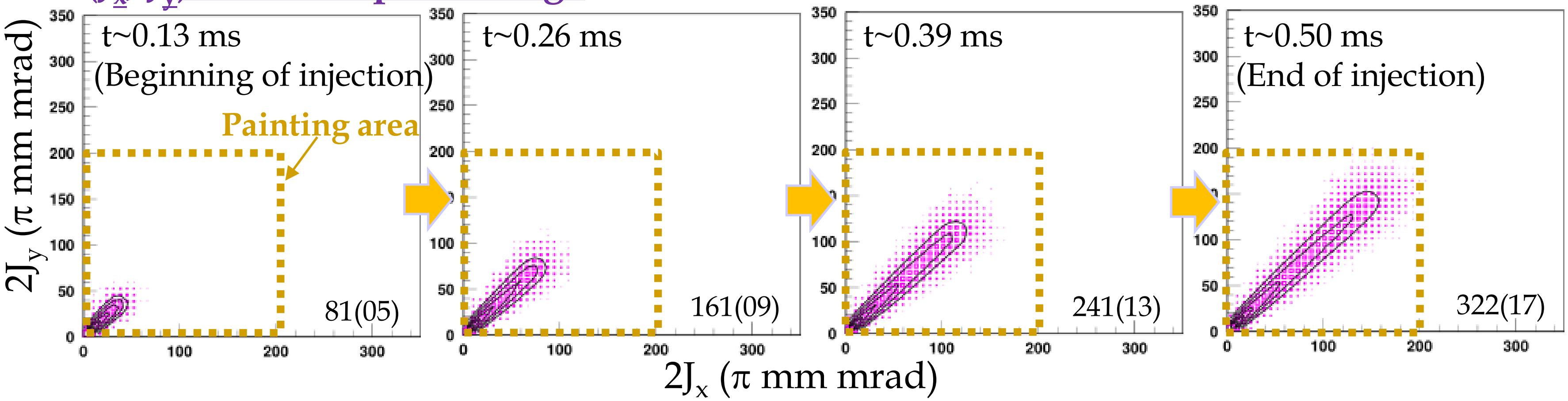
2d plot of the horizontal and vertical actions; mechanism of the above beam loss



- ✓ Multi-turn injection painting is applied; the injection beam is painted from the middle to the outside on both horizontal and vertical planes (Correlated painting).
- ✓ To this direction of beam painting, the emittance exchange occurs in the orthogonal direction; it leads to significant emittance diffusion.

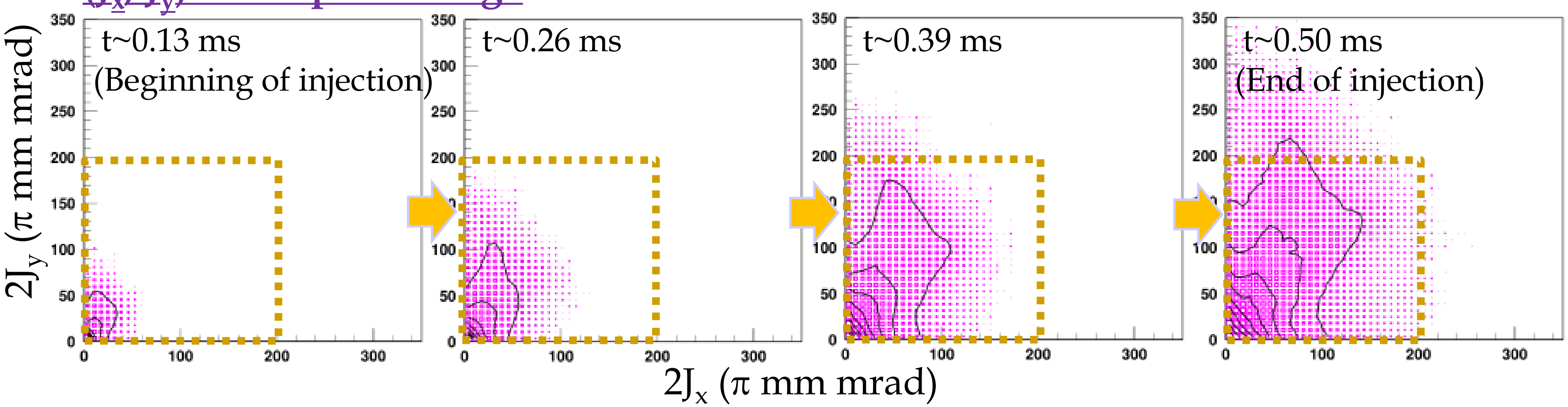
Betatron actions (J_x, J_y) during injection

(J_x, J_y) without space charge



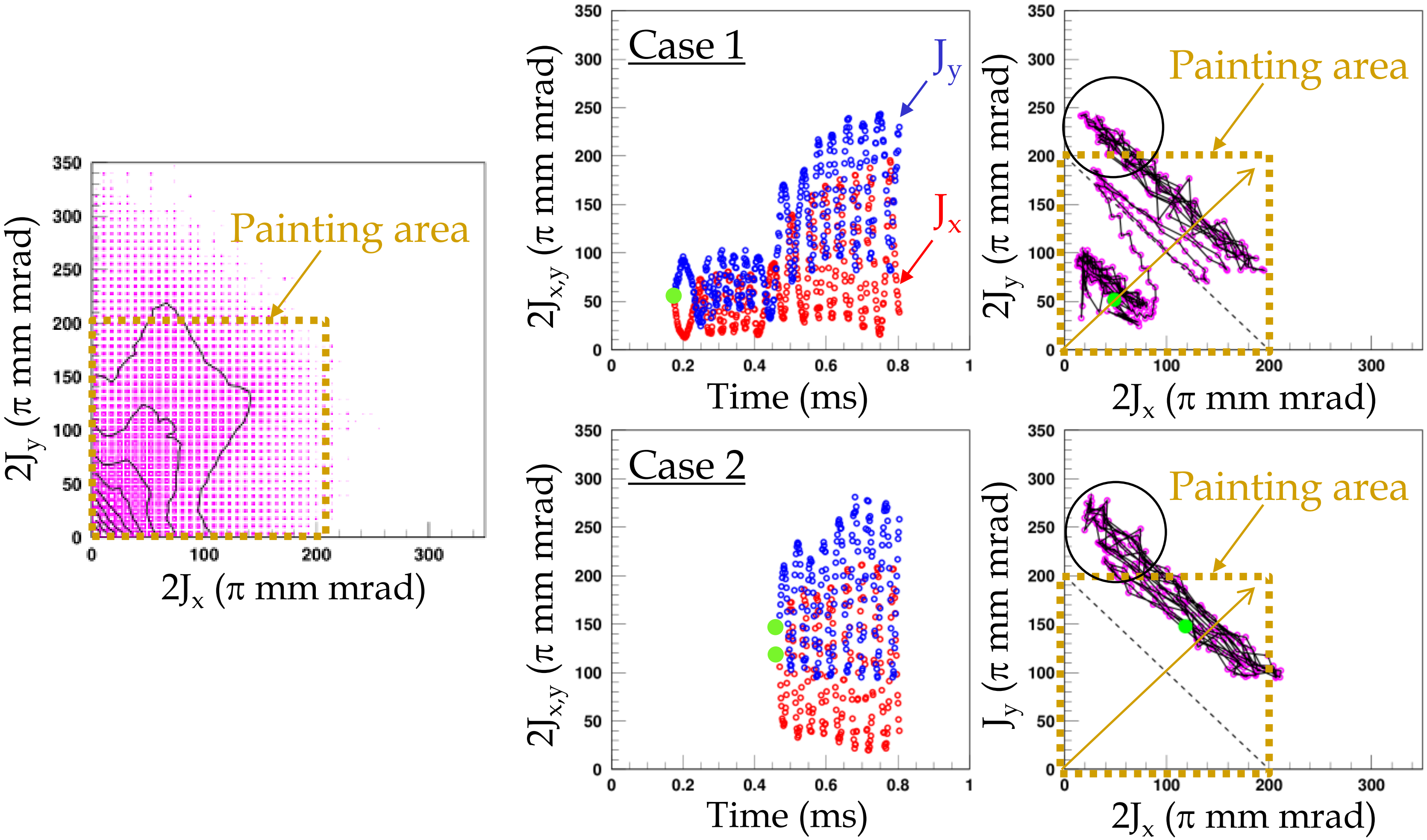
✓ The above situation significantly changes when the space charge is turned on.

(J_x, J_y) with space charge



✓ We can see a significant diffusion of particles swerving from the path of beam painting, and it finally causes emittance growth over the painting area.

Single-particle motion of one macro-particle leading to large emittance growth

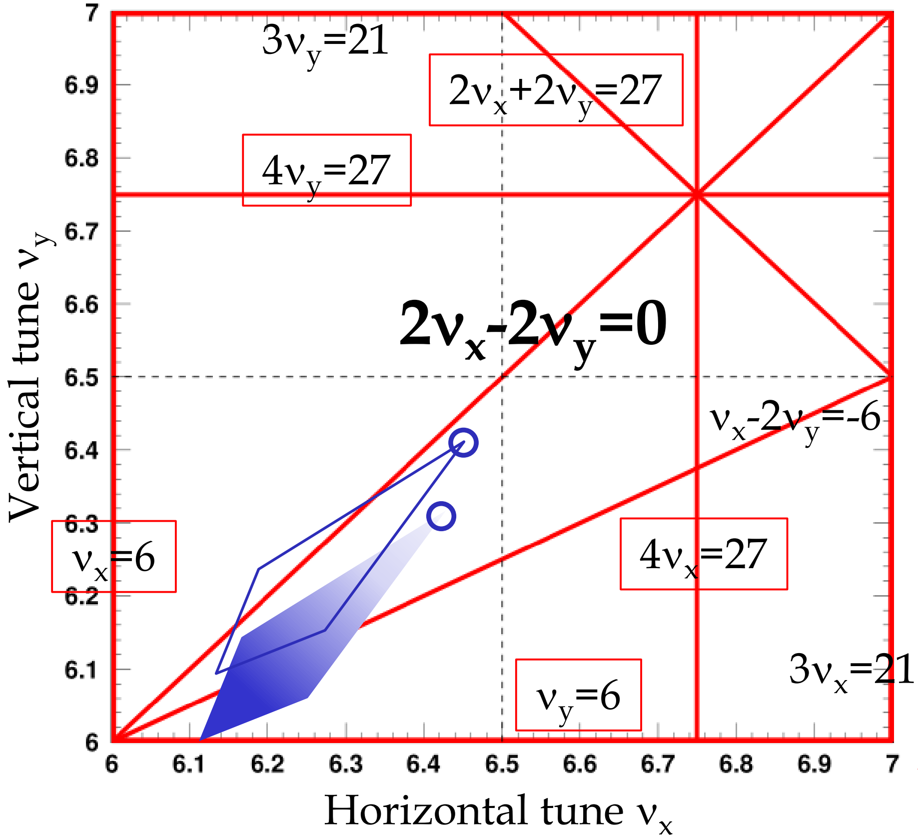


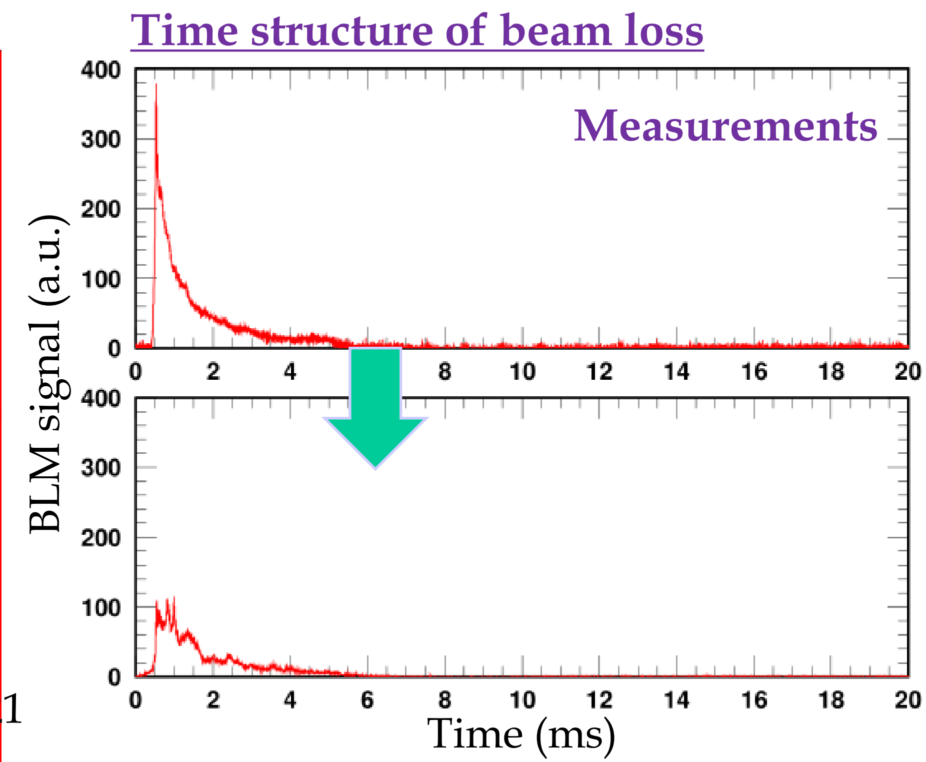
- ✓ This figure clearly shows the emittance growth is mainly caused by the emittance exchange which occurs perpendicularly to the path of beam painting.
- ✓ This is the mechanism of the observed beam loss.

Change of the operating point

- ✓ We found several measures against the beam loss;
  - Reduction of the painting area,
  - Introduction of anti-correlated painting,
  - Change of the operation point to get larger separation from $2\nu_x-2\nu_y=0$.

Now applied!



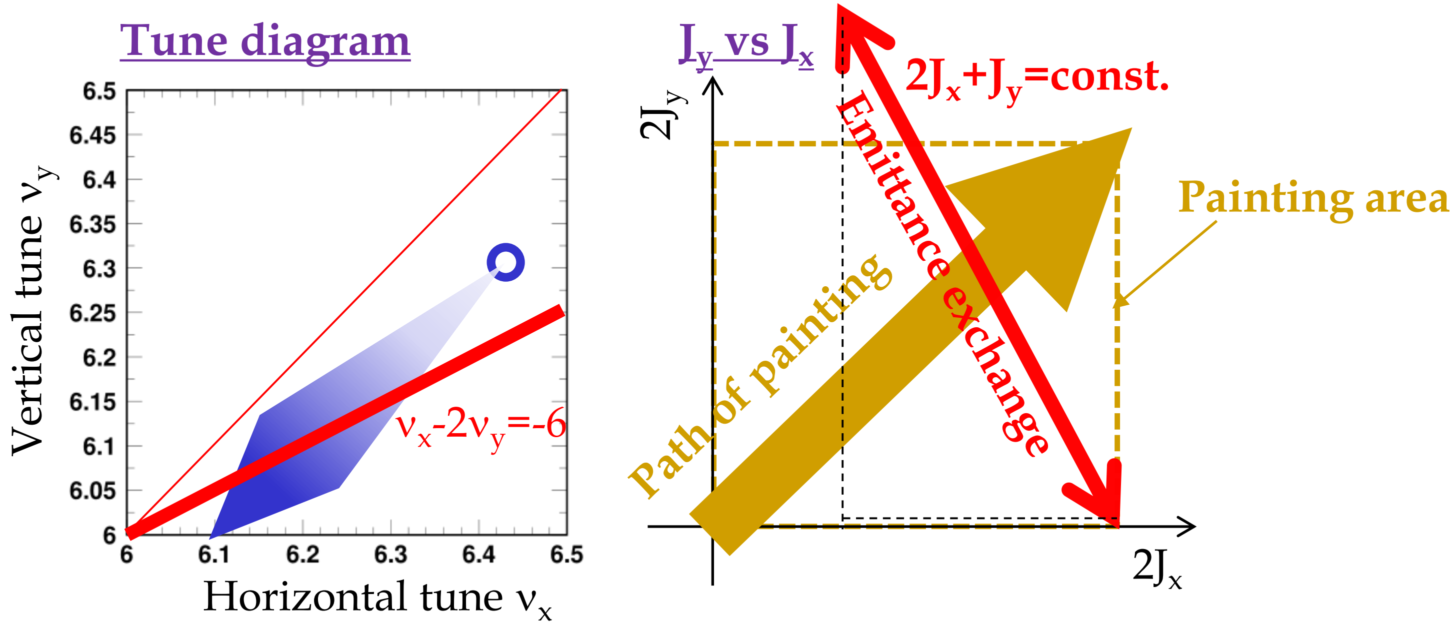


✓ This tune change mitigated the effect of $2\nu_x-2\nu_y=0$, and well reduced the beam loss.

✓ But the modified tune enhanced the effect of $\nu_x-2\nu_y=-6$.

✓ The residual beam loss was mainly from $\nu_x-2\nu_y=-6$.

Effect of the ν_x-$2\nu_y$=-6 resonance



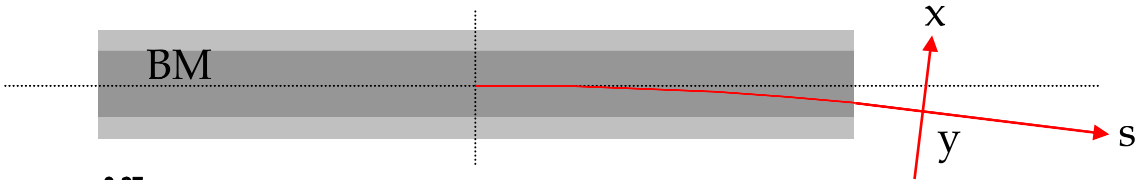
✓ ν_x-$2\nu_y$=-6;

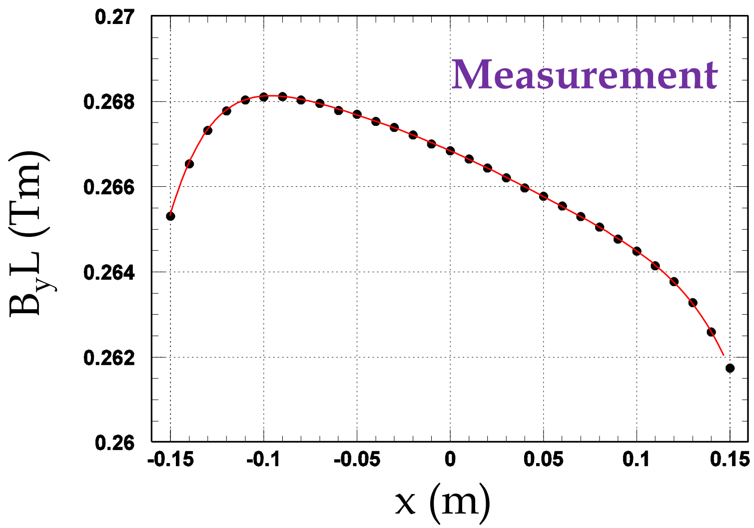
- structure resonance,
- affecting the beam especially at low energies where a large space-charge detuning is generated,
- causing emittance exchange ($2J_x$+J_y=const.), leading to larger emittance growth on the vertical plane.

Source of the ν_x-$2\nu_y$=-6 resonance

- ✓ The main source of the ν_x-$2\nu_y$=-6 resonance is
  the sextupole field components intrinsic in the bending magnets.

Result of the magnetic field measurement for the bending magnet





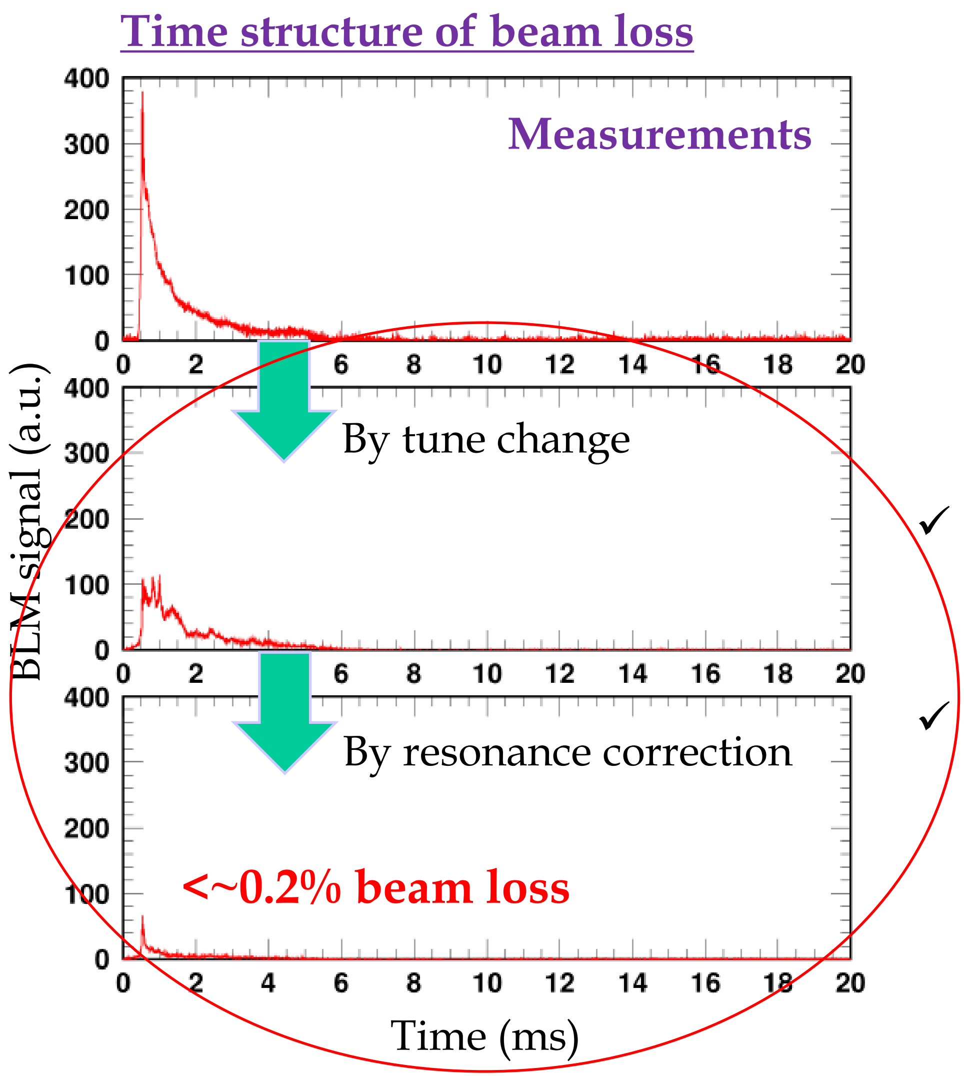
K_0= 2.618E-1
K_1=-2.023E-2 (m^{-1})
K_2=-1.006E-1 (m^{-2})

- ✓ Driving term of ν_x-$2\nu_y$=-6; $G_{1,-2,-6}e^{j\xi} = -\frac{\sqrt{2}}{8\pi}\oint\sqrt{\beta_x\beta_y^2}\,k_2 e^{j(\psi_x-2\psi_y-(\nu_x-2\nu_y+6)\theta)}ds = 0.47+0.11j$

- ✓ The driving term can be compensated with two families
  of sextupole magnets with the following modest strengths;

$\boxed{\text{SDA, SDB } K_2\text{=0.066 } (m^{-2})}$

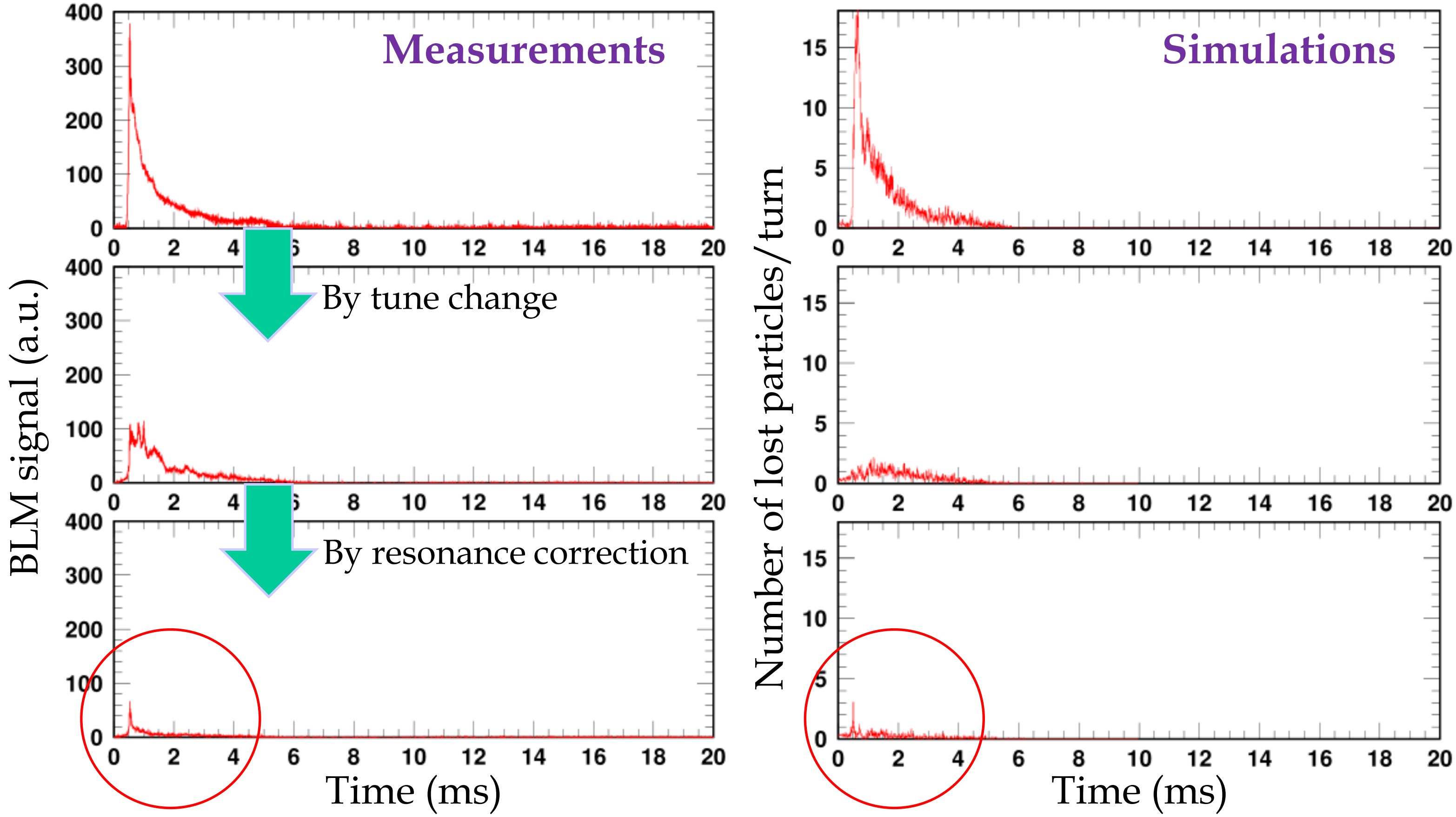
Introduction of 3rd-order resonance correction



- ✓ Based on the above analysis, two families of sextupole magnets were introduced for the resonance correction.
- ✓ By this way, the beam loss was well reduced; the residual beam loss was estimated to be the order of 10^{-3} only around the injection energy.

Comparison with the numerical simulation results

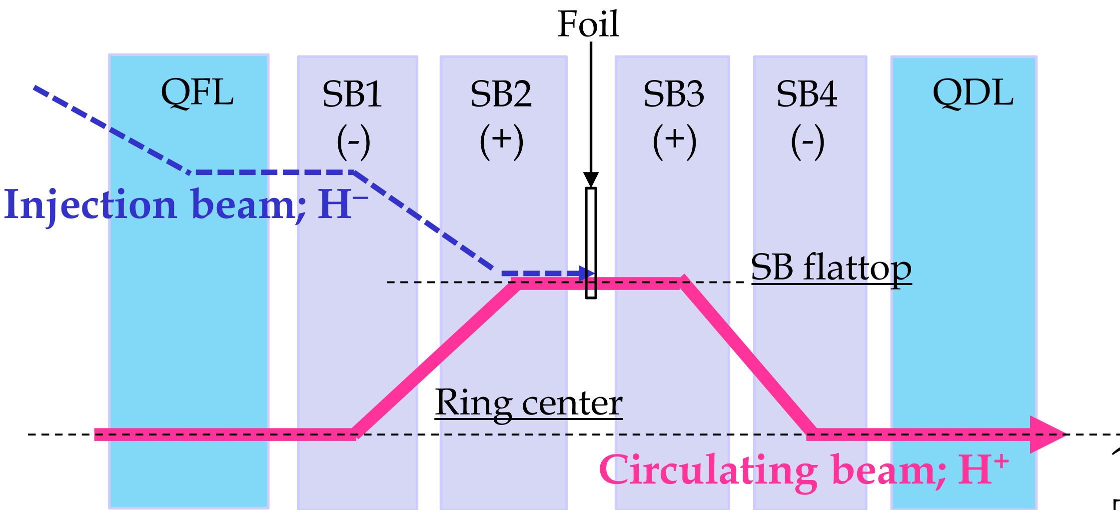
Time structure of beam loss



- ✓ The numerical simulation well reproduced the empirical beam loss and found two major sources of the residual beam loss;
  - **(1) Effect of $3\nu_x=19$ (random resonance) driven by sextupole field components intrinsic in the injection bump magnets (SB1-4),**
  - **(2) Residual effect of $\nu_x-2\nu_y=-6$ (structure resonance) on off-momentum particles.**

Source of the residual beam loss - (1) -

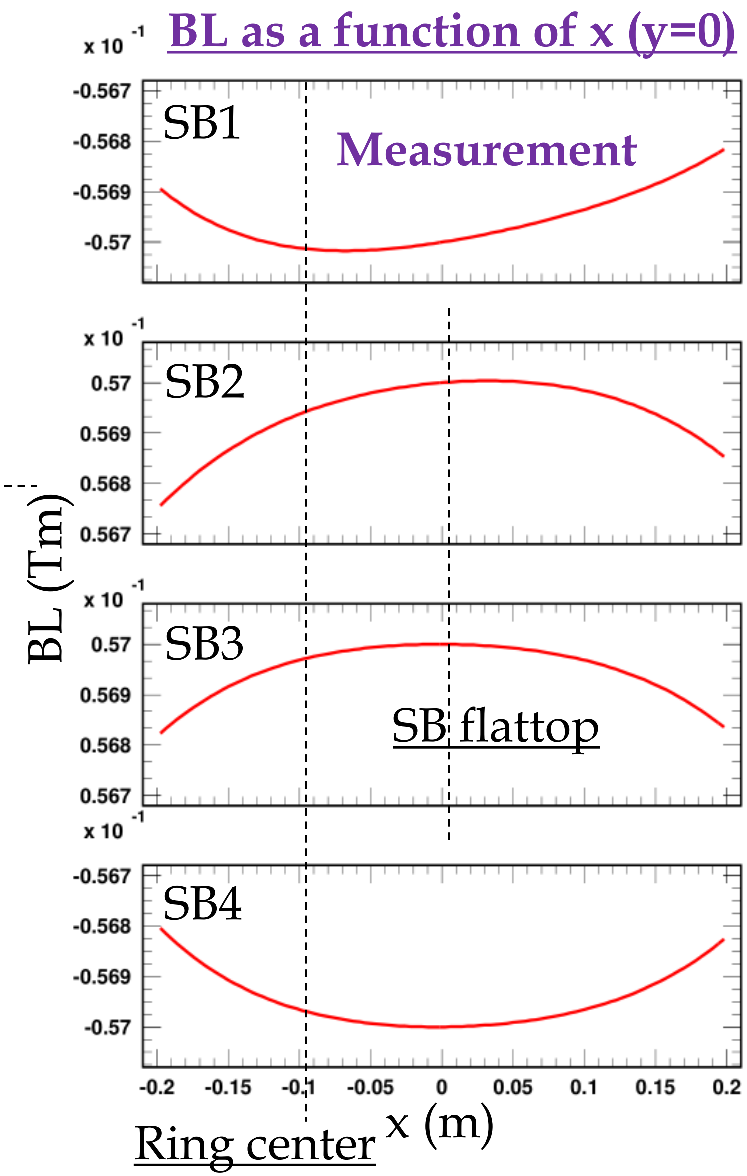
Orbit bump for injection



- ✓ Four sets of same-type pulsed dipole magnets (SB1-4) are used for forming an injection orbit bump of Δx=101 mm.
  - ➢ 0.5 ms flattop for multi-turn (307 turns) injection
  - ➢ 0.35 ms fall time

✓ Each SB has a significant sextupole component.

BL as a function of x (y=0)



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
  are cancelled out 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!

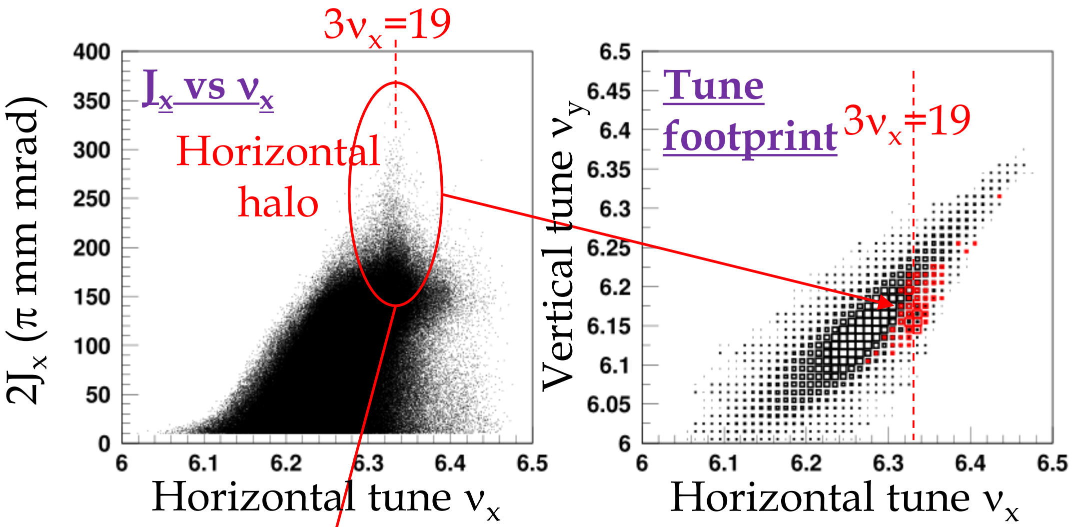
"ACTUAL" situation

- ✓ 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.

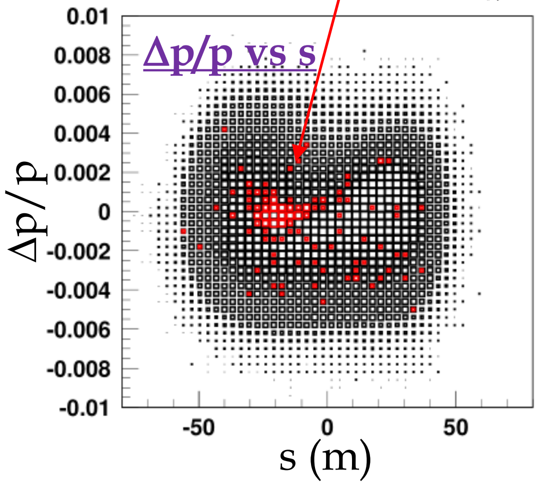
⇓

- ✓ The residual sextupole component (K_2=0.012 m^{-2}), not canceled out, excites $3\nu_x$=19, making a slight 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.

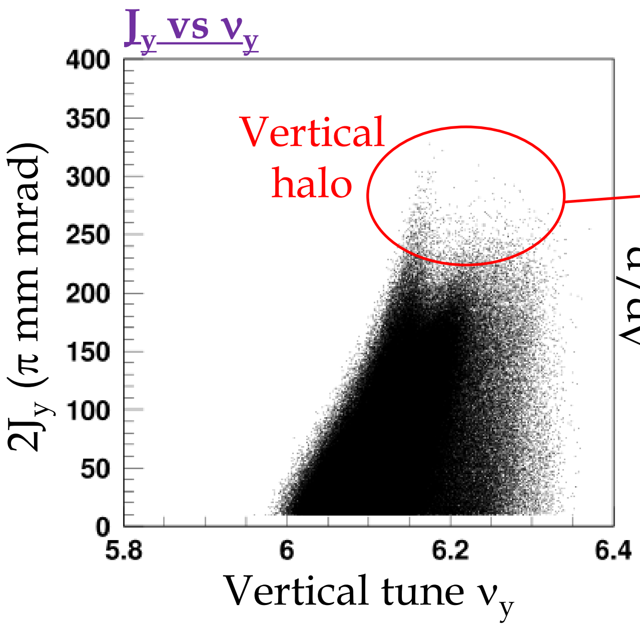
✓ The tunes of such particles do not change widely turn by turn.

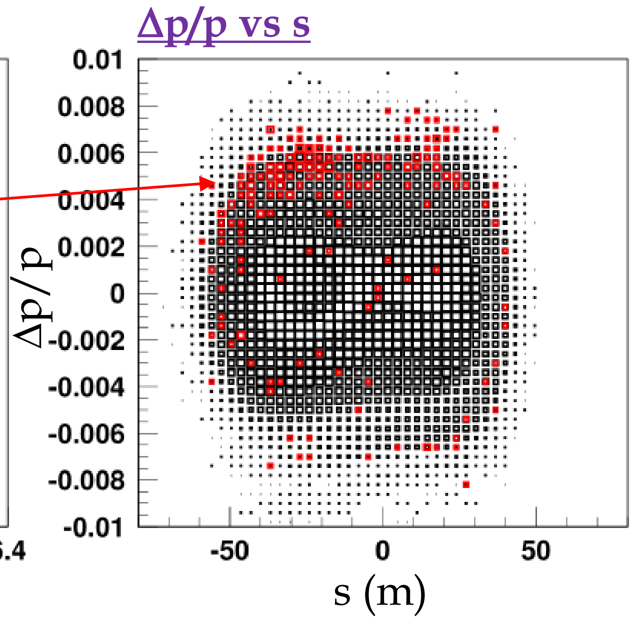
- The $\Delta p/p$ of such particles do not change widely.
  → The turn-by-turn change of the chromatic tune shift is restrictive.
- The effect of space charge on such particles are almost constant due to the flat bunch distribution.
  → The turn-by-turn change of the space-charge tune shift is also restrictive.

✓ A part of such 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 part of the residual beam loss.

Another source of the residual beam loss; (2)





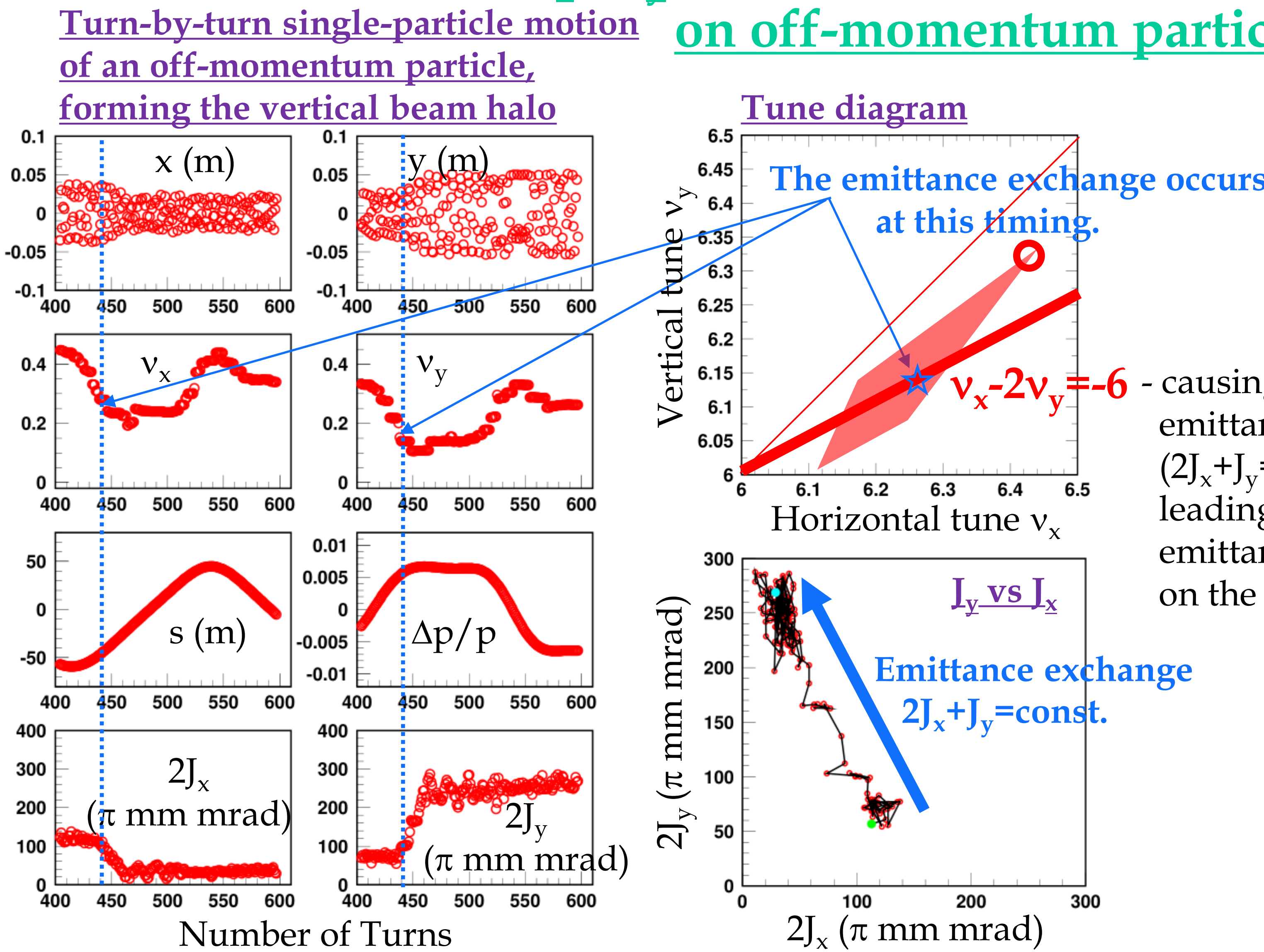
calculated at t~1.2 ms

- ✓ Most of the large amplitude particles found on the vertical plane move around the outer region of the longitudinal phase space.
- ✓ They are off-momentum particles.
- ✓ We investigated a turn-by-turn single-particle motion for such particles.

⬇

- ✓ We found the residual effect of the ν_x-$2\nu_y$=-6 resonance on off-momentum particles generates the vertical beam halo.

Residual effect of the ν_x-$2\nu_y$=-6 resonance on off-momentum particles

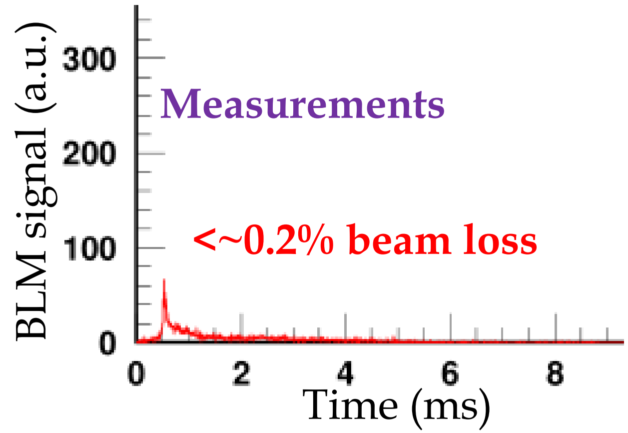


- causing emittance exchange ($2J_x+J_y$=cont.), leading to larger emittance growth on the vertical plane.

- ✓ The resonance correction is applied for ν_x-$2\nu_y$=-6, but it is just for on-momentum particles.
- ✓ The effect of the resonance is still left for off-momentum particles.

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

Result of the parameter optimization for the 1-MW beam operation



- ✓ The current residual beam loss in the 1-MW beam operation is mainly from the incoherent betatron resonances; $3\nu_x$=19 & $\nu_x+2\nu_y$=19.
- ✓ We expect that the residual beam loss does not lead to serious machine activations.
  - The amount of the residual beam loss is 10^{-3} level only around the injection energy, which is sufficiently small, and most of it is well localized at the collimator section.
- ✓ We have recently demonstrated a continuous 10.5-hour 1-MW beam operation at 25 Hz using the latest operational parameters.
  - The number of beam-stops was only 3 times due to the RFQ trip.
  - No significant increase of the machine activation was detected.
- ✓ The accelerator itself including the linac is ready for the 1-MW design beam operation.

- ✓ **This success of the 1 MW beam operation opened a possibility of further beam power ramp-up beyond 1 MW.**

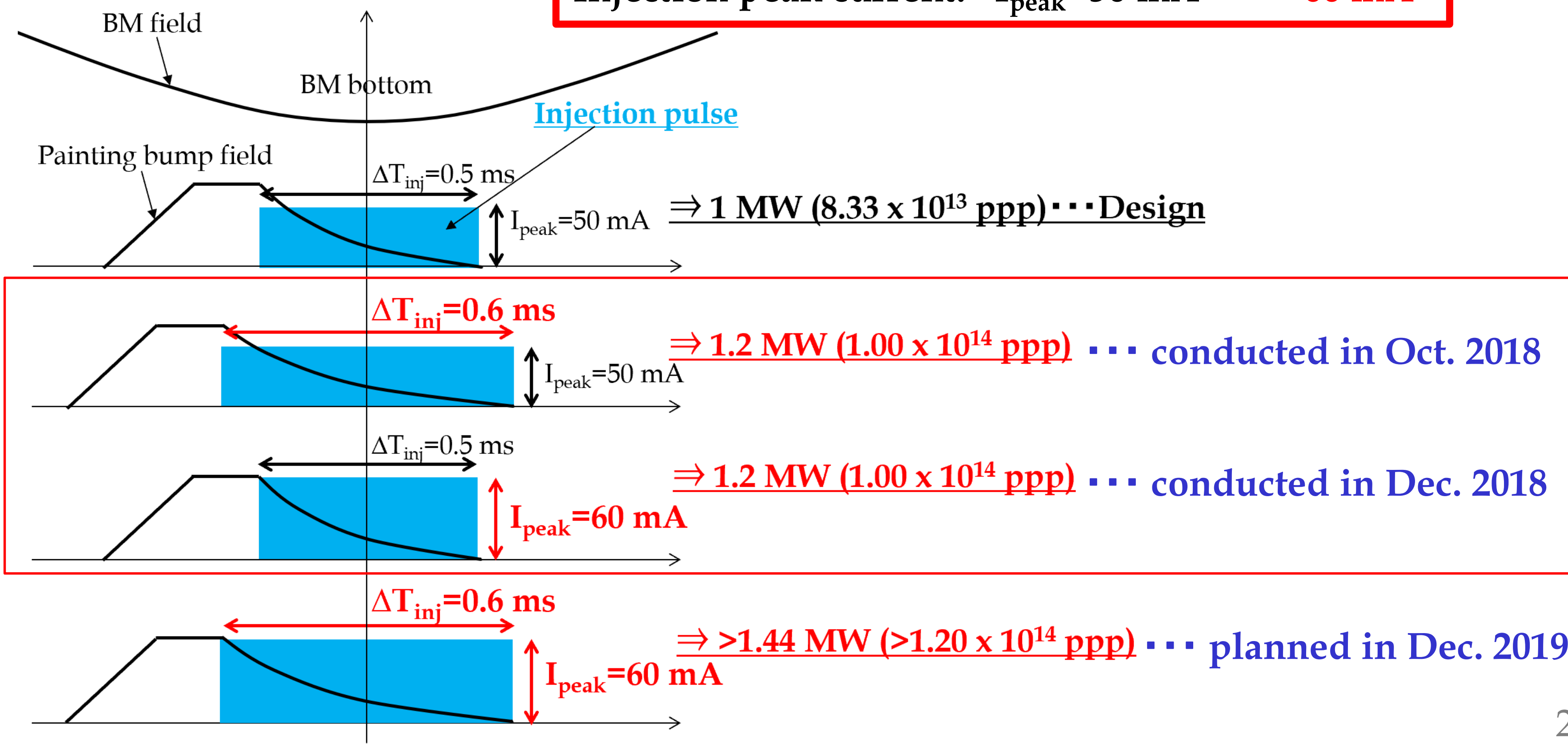
3. Recent efforts toward further beam power ramp-up beyond 1 MW

Ways of beam power ramp-up

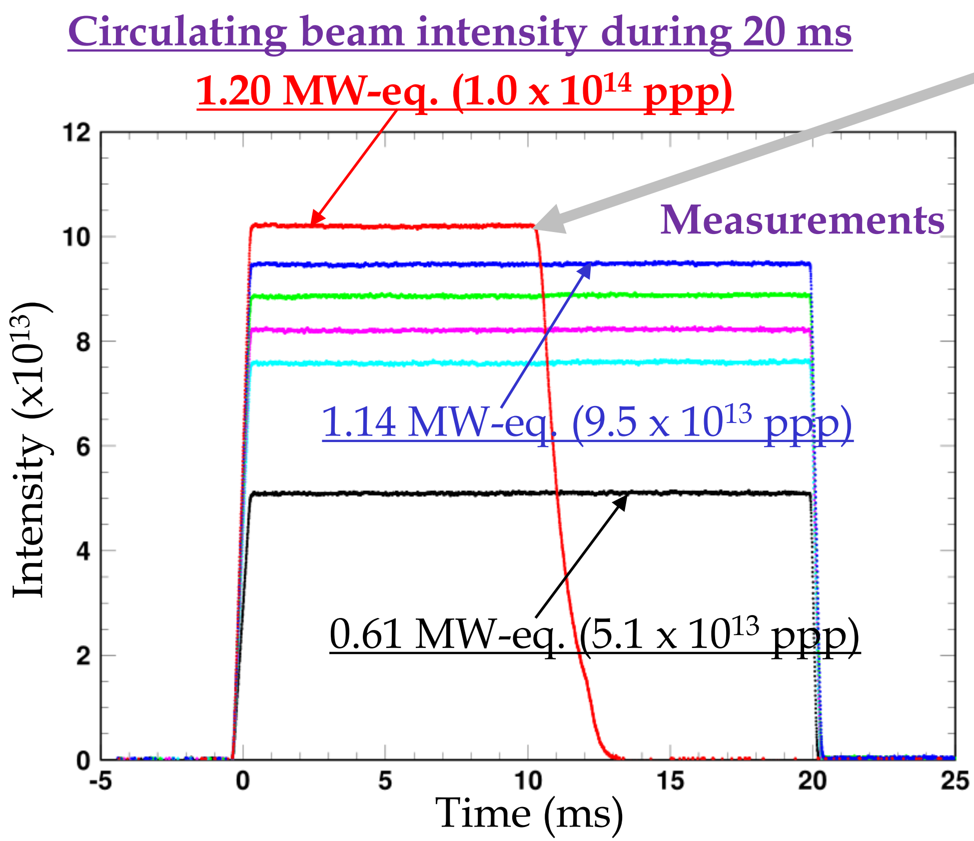
- ✓ We have recently initiated further high-intensity beam tests aiming for a higher beam power beyond 1 MW looking ahead to future upgrades of the J-PARC such as the construction of the 2nd target station.
- ✓ The initial goal is to achieve 1.2~1.5-MW-eq. high-intensity beam accelerations within permissible beam loss levels.

Injection pulse length: ΔT_{inj}=0.5 ms → 0.6 ms
Injection peak current: I_{peak}=50 mA → 60 mA

Required injection beams



Beam test with "I_{peak}=50 mA & ΔT_{inj}=0.6 ms"



✓ **RF tripped due to the limit of the RF anode power supply.**

- For higher beam intensity, larger beam loading compensation is required.
- The 1.2-MW case exceeded the limit of the RF anode power supply.
- To realize the 3-GeV acceleration, we need to reduce the required anode current; it can be realized by adjusting the resonant frequency of the RF cavity.
- We will take such measures against the RF trip in this summer maintenance period.
- After that, in Dec. 2019, we will try 3-GeV acceleration again for the beam intensity of >1.2 MW.

✓ We achieved the 3-GeV acceleration for the beam intensities of up to 1.1 MW.

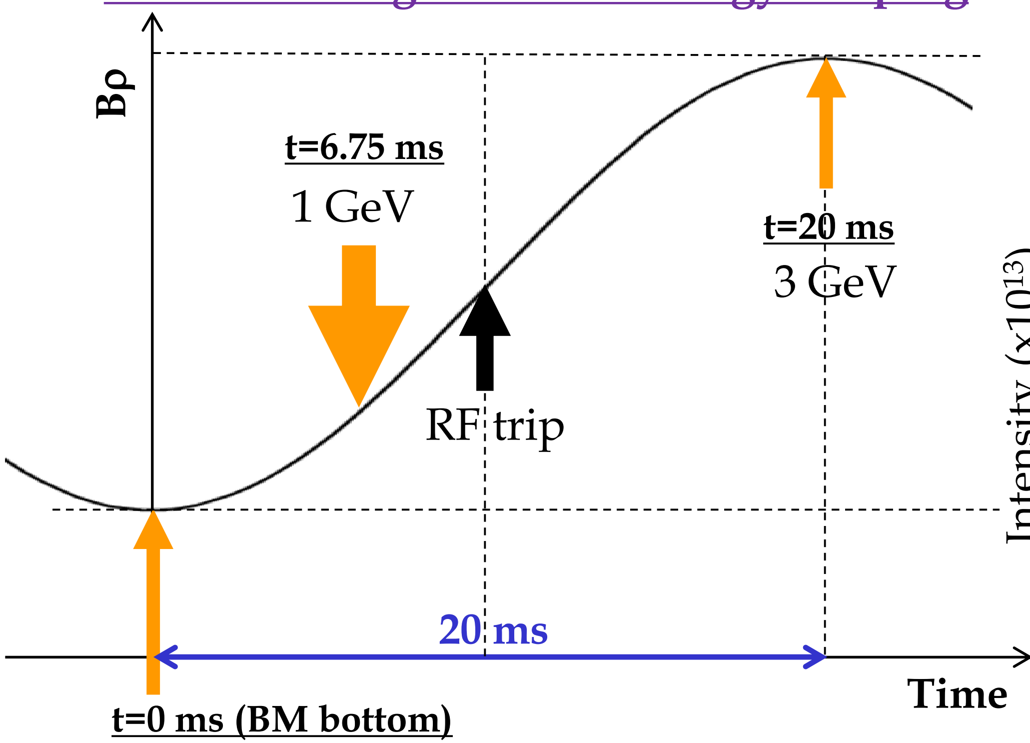
✓ The 3-GeV acceleration for the 1.2-MW beam was not reached. (But we achieved beam acceleration above 1 GeV.)

✓ Beam loss usually occurs for low energy region (<1 GeV).
⇒ We were able to complete sufficient beam loss study even for the 1.2-MW beam.

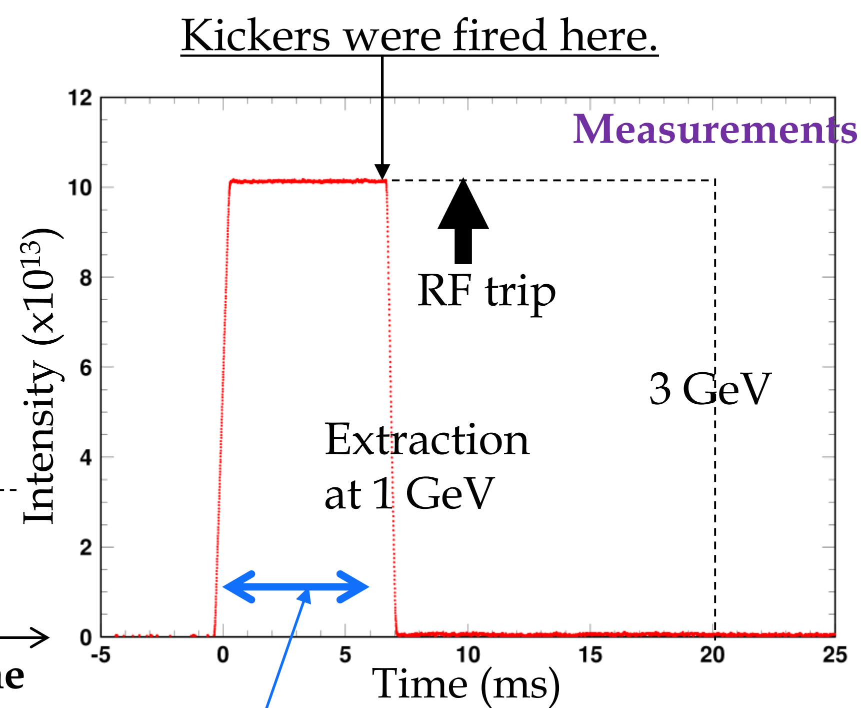
1-GeV extraction

✓ At the start of the beam study for the 1.2 MW beam, we established 1-GeV extraction.

Schematic diagram of the energy ramping



Circulating beam intensity



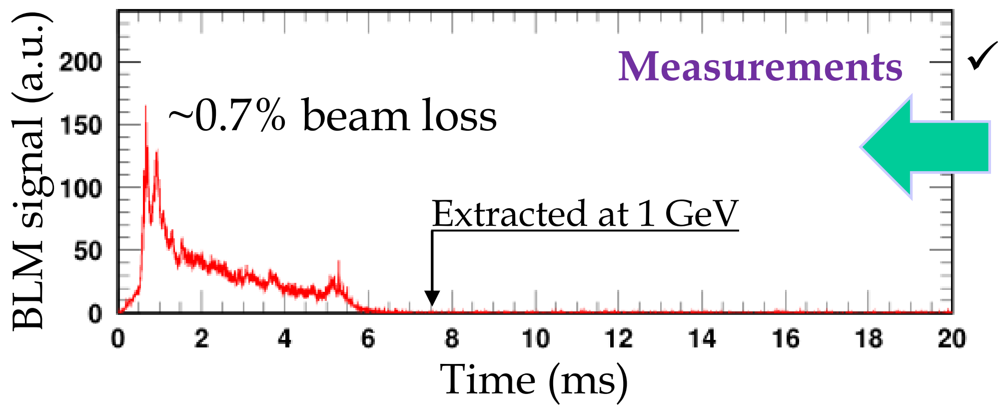
✓ To avoid unnecessary RF trip and beam loss, the beam was extracted at 1 GeV before the RF trip, and properly transported to the beam dump.

✓ After establishing this system, we performed detailed beam loss study for the 1.2 MW beam.

- The beam loss appears only for the first 6 ms, so sufficient beam loss study can be carried out even for this condition.

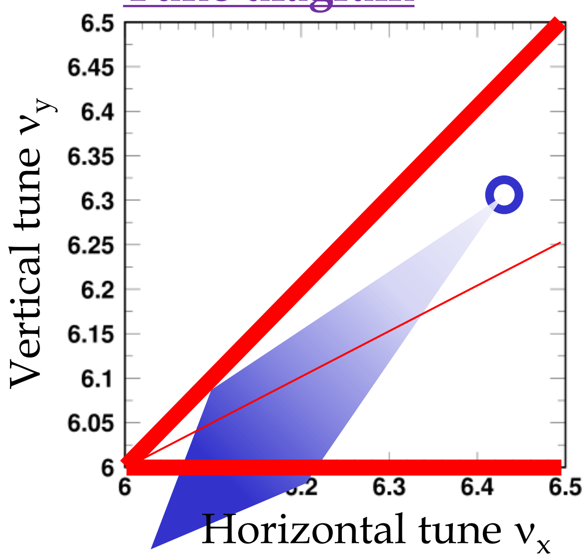
Beam loss observed for the 1.2-MW beam

Time structure of beam loss



- ✓ First, we investigated the situation of beam loss for the 1.2 MW beam using the operational parameters optimized for the 1-MW beam.

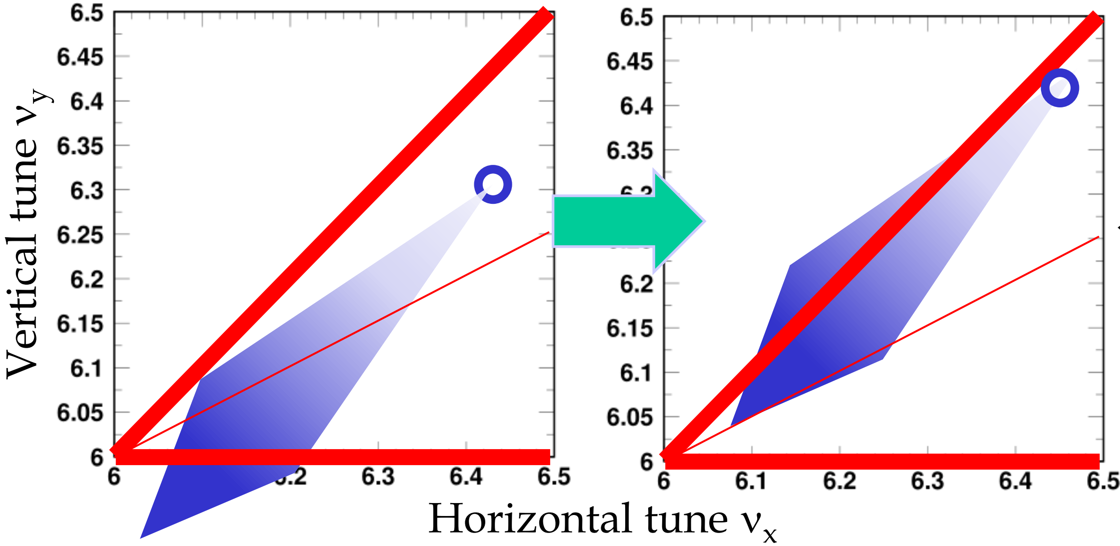
Tune diagram



- ✓ The beam loss appeared to occur due to a low-order systematic resonance existing around $\nu=6$; $2(\nu_0-C_2\Delta\nu)=12$??

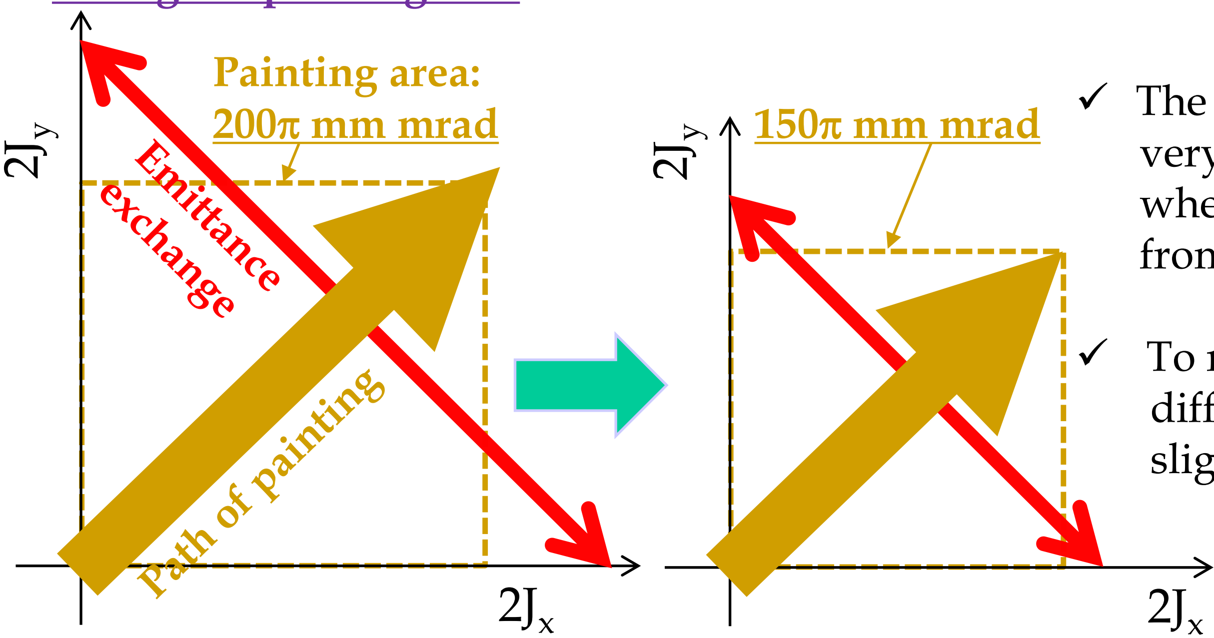
Parameter optimization for beam loss mitigation

Change of operating point



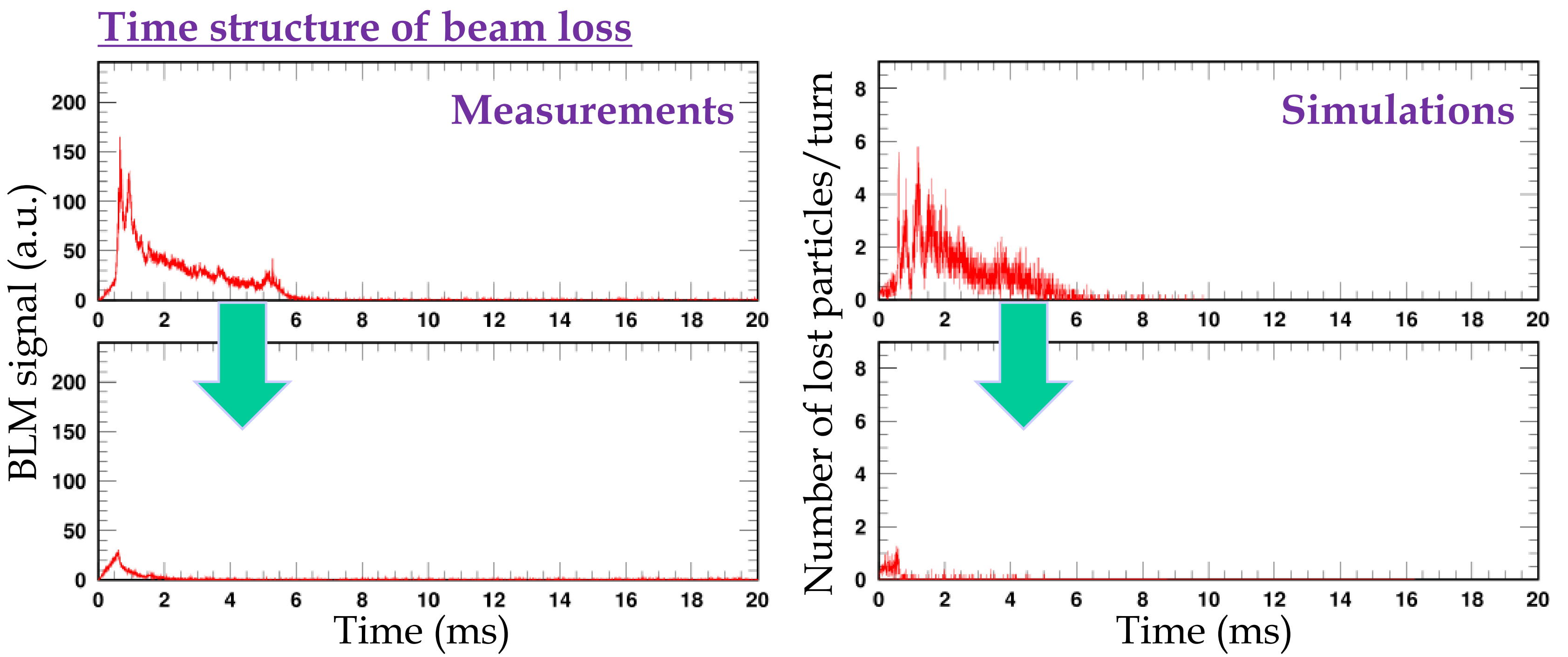
- ✓ To get larger separation from ν=6, the operating point was modified.

Change of painting area



- ✓ The modified operating point is very close to $2\nu_x$-$2\nu_y$=0, where emittance diffusion arising from emittance exchange occurs.
- ✓ To reduce the scale of emittance diffusion, the painting area was slightly reduced.

Beam loss observed for the 1.2-MW beam after the parameter optimization



✓ The beam loss was well reduced to the order of 10^{-3} even for the 1.2 MW beam, as predicted by the numerical simulations.

4. Intensity limit of the J-PARC RCS ??

From the beam dynamics viewpoint . . .

- Beam intensity achievable?
- What finally limits the beam intensity?

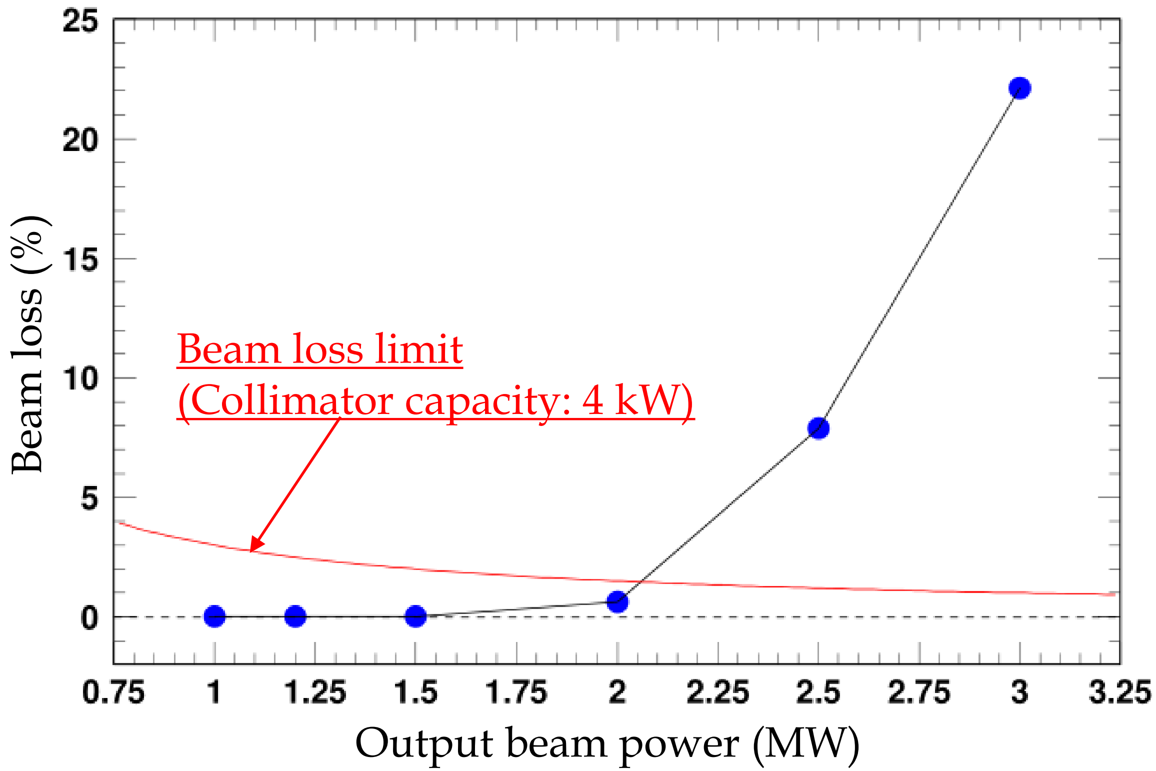
✓ In order to explore the intensity limit of the RCS, we have been performing beam simulations of up to 3 MW.

1~3 MW simulations

Intensity dependence of beam loss

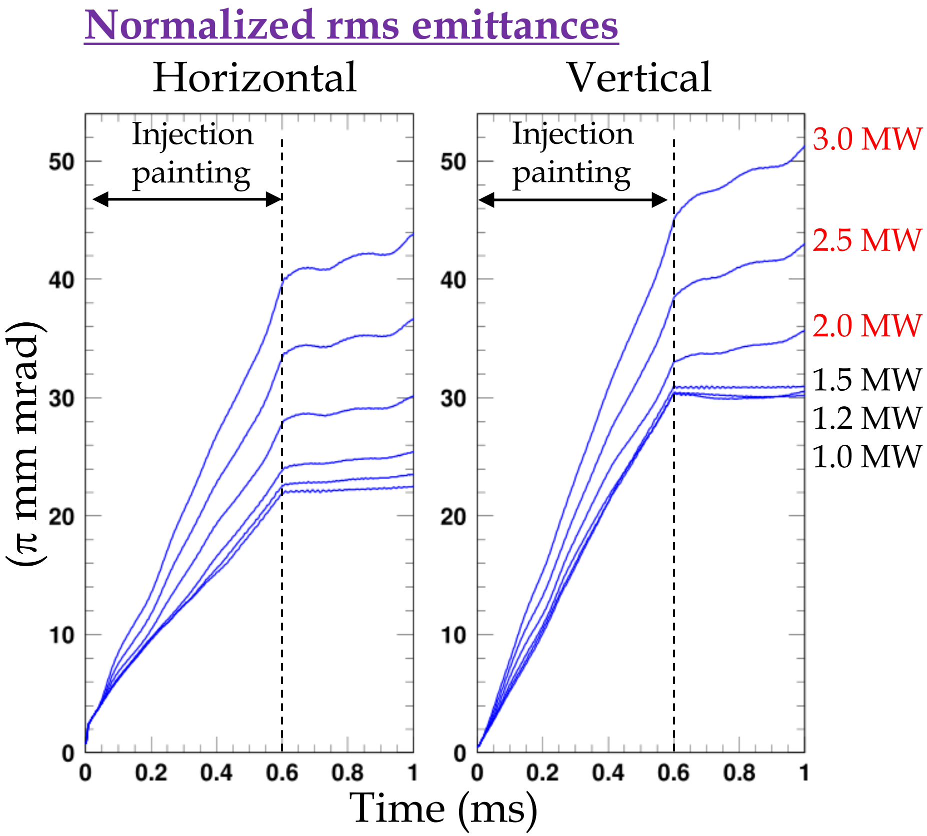
Assuming . . .

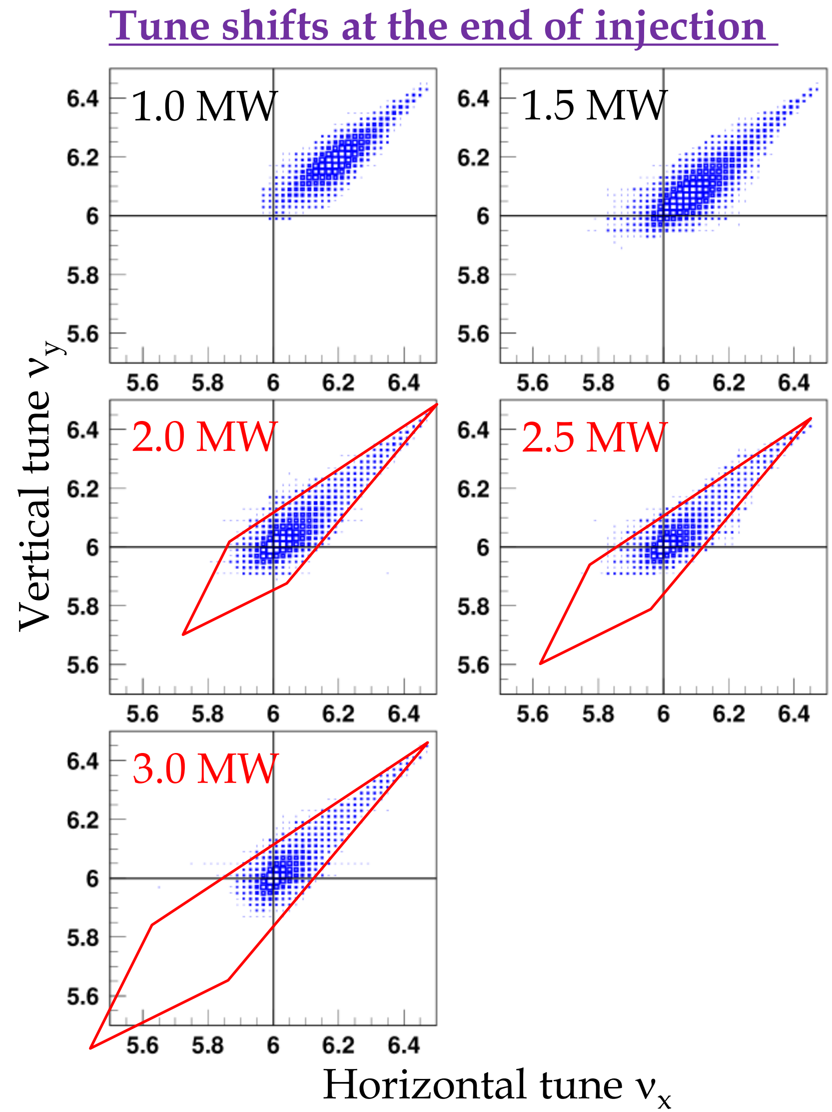
- Ideal linear lattice with no error
- Operational parameters optimized in the actual 1.2 MW beam test
  - Operating point: (6.45, 6.42)
  - Transverse painting area: 150π mm mrad



✓ Beam loss increases sharply after 2 MW-eq beam intensity.

Emittance growth during injection

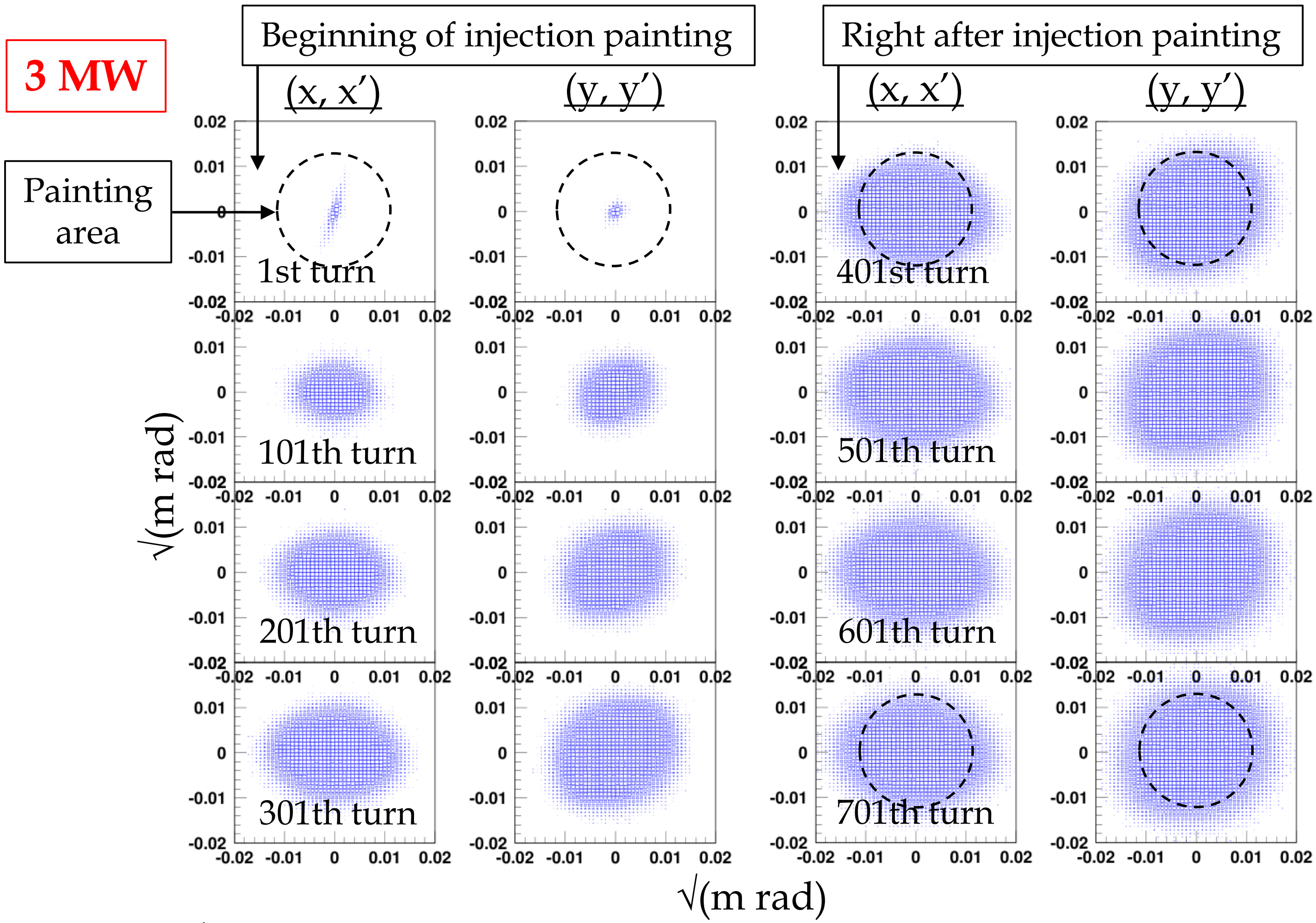




- ✓ Emittance growth is enhanced sharply after 2 MW-eq beam intensity.
- ✓ This emittance growth prevents the increase of tune shift after 2 MW-eq beam intensity; the ν=6 lines look like a barrier.

What causes the emittance growth?

Evolution of the transverse phase-space distribution



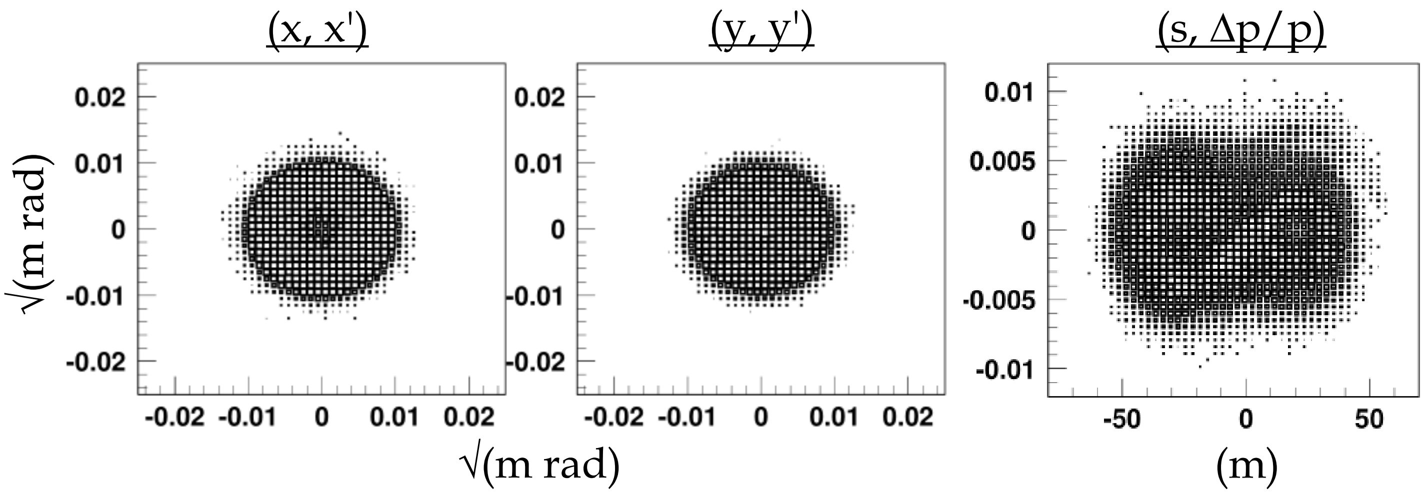
✓ We cannot get useful information from this;
It is possible that **injection painting makes it difficult to find the mechanism of the emittance growth**.

✓ We next performed simpler simulations **omitting the injection painting process**; **1-turn injection simulations.**

1-turn injection simulations

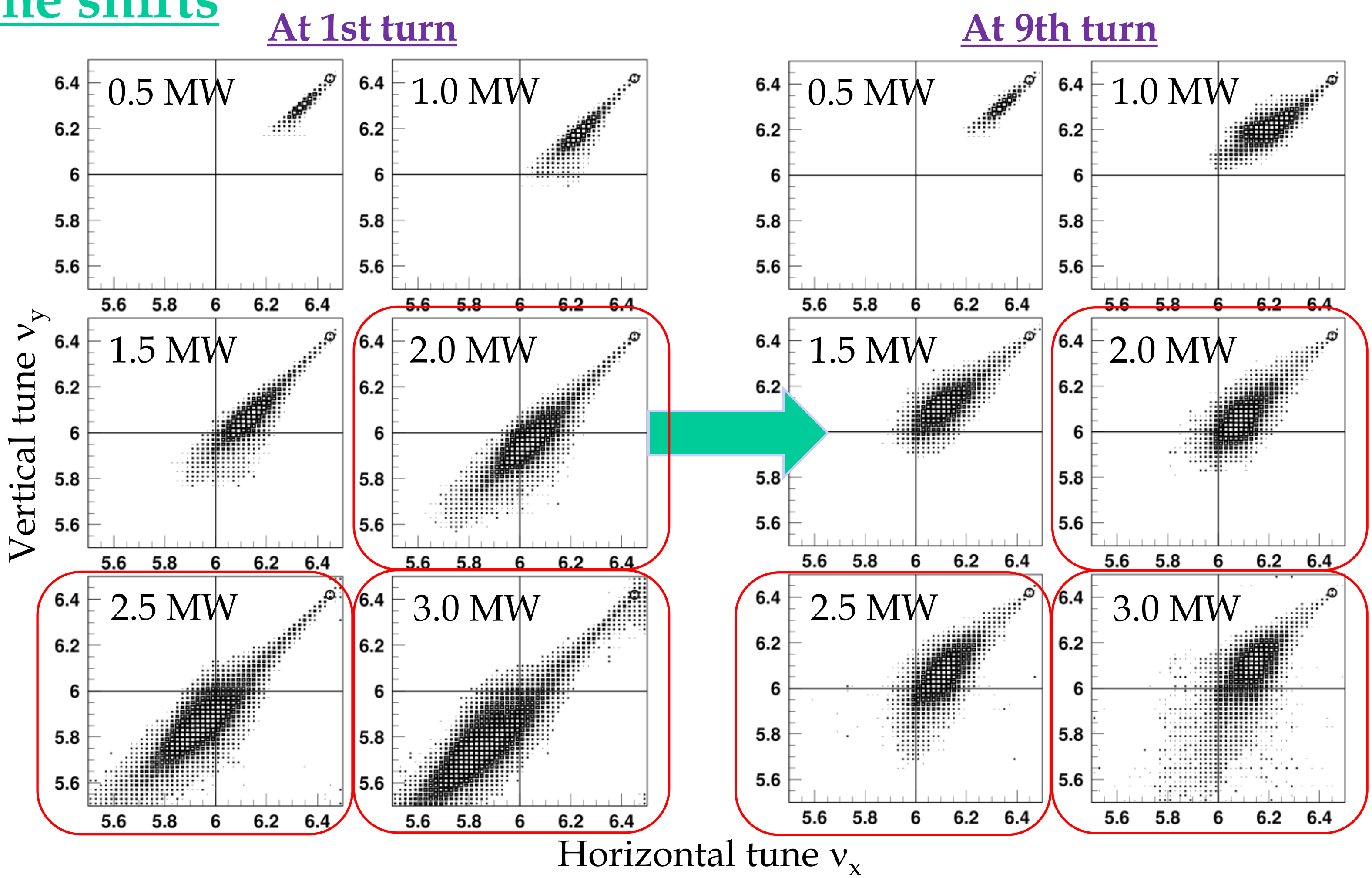
- ✓ The initial 6d distributions were made beforehand by separately performing injection painting simulation with no space charge.

Initial 6d distributions



- ✓ The above beam was 1-turn injected with space charge, and its subsequent behavior was investigated.
- ✓ **The purpose of the simulation is to get a hint as to the cause of the emittance growth in the painting process.**

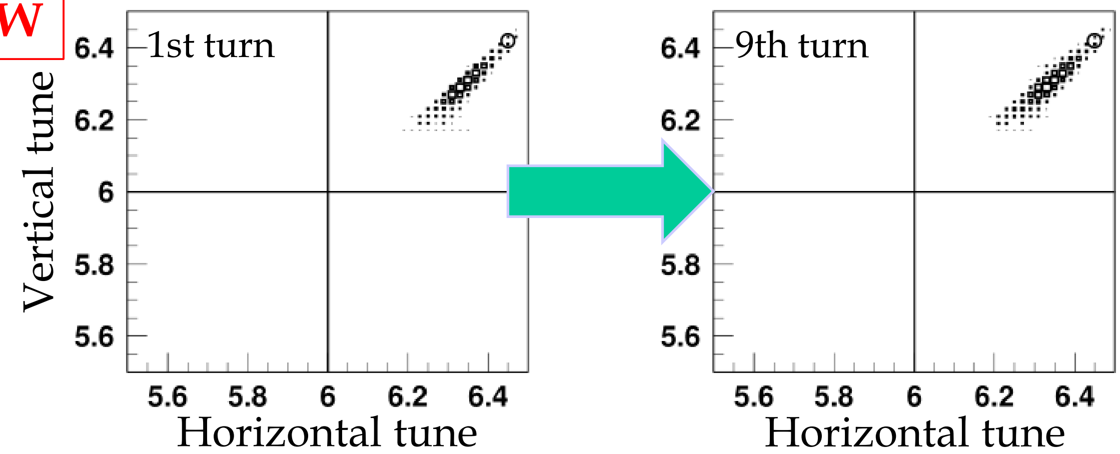
Tune shifts



- ✓ The tune shift at the 1st turn is directly proportional to the beam intensity, but the situation drastically changes after 9 turns.
  - The large tune shift reaching below ν=6 is quickly pushed back above ν=6.
  - It is very similar to the previous case.
- ✓ This means large emittance growth occurs for the beam intensities of >2 MW similarly to the previous case.

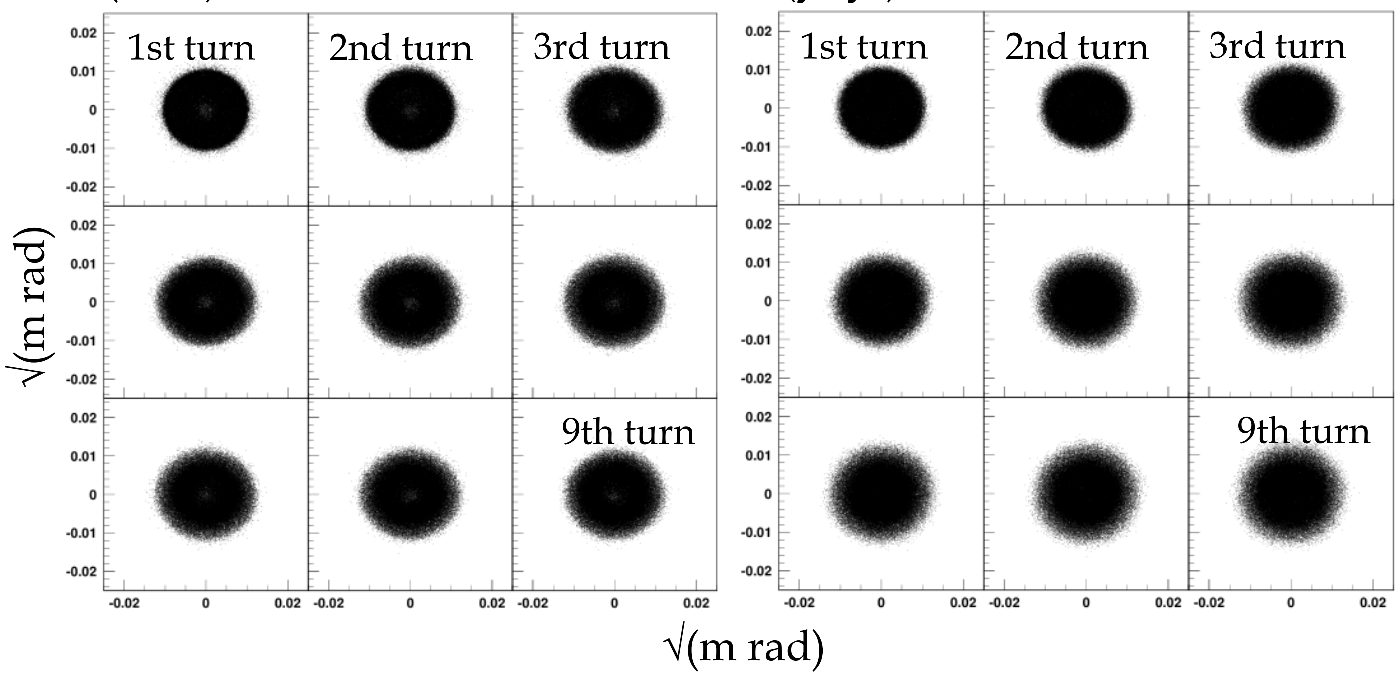
Evolution of the transverse phase space distribution

0.5 MW



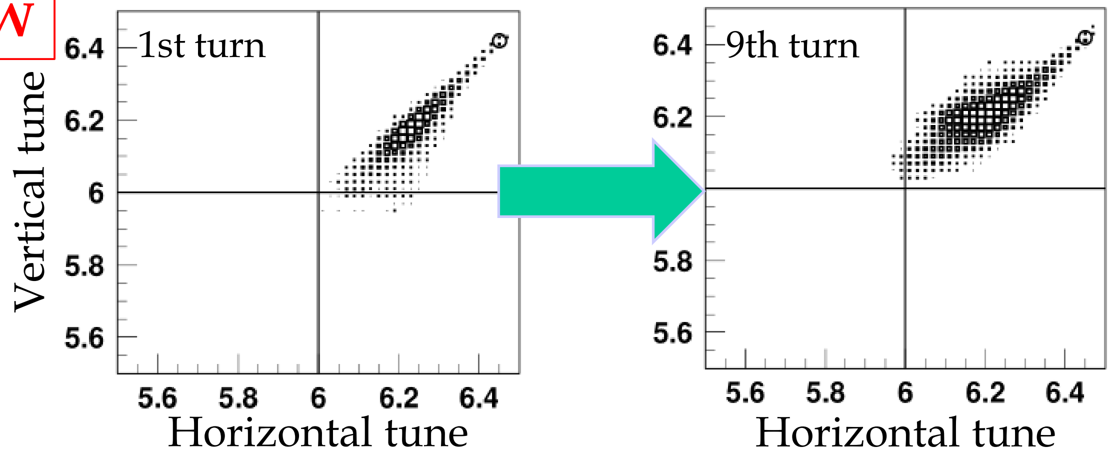
(x, x′)

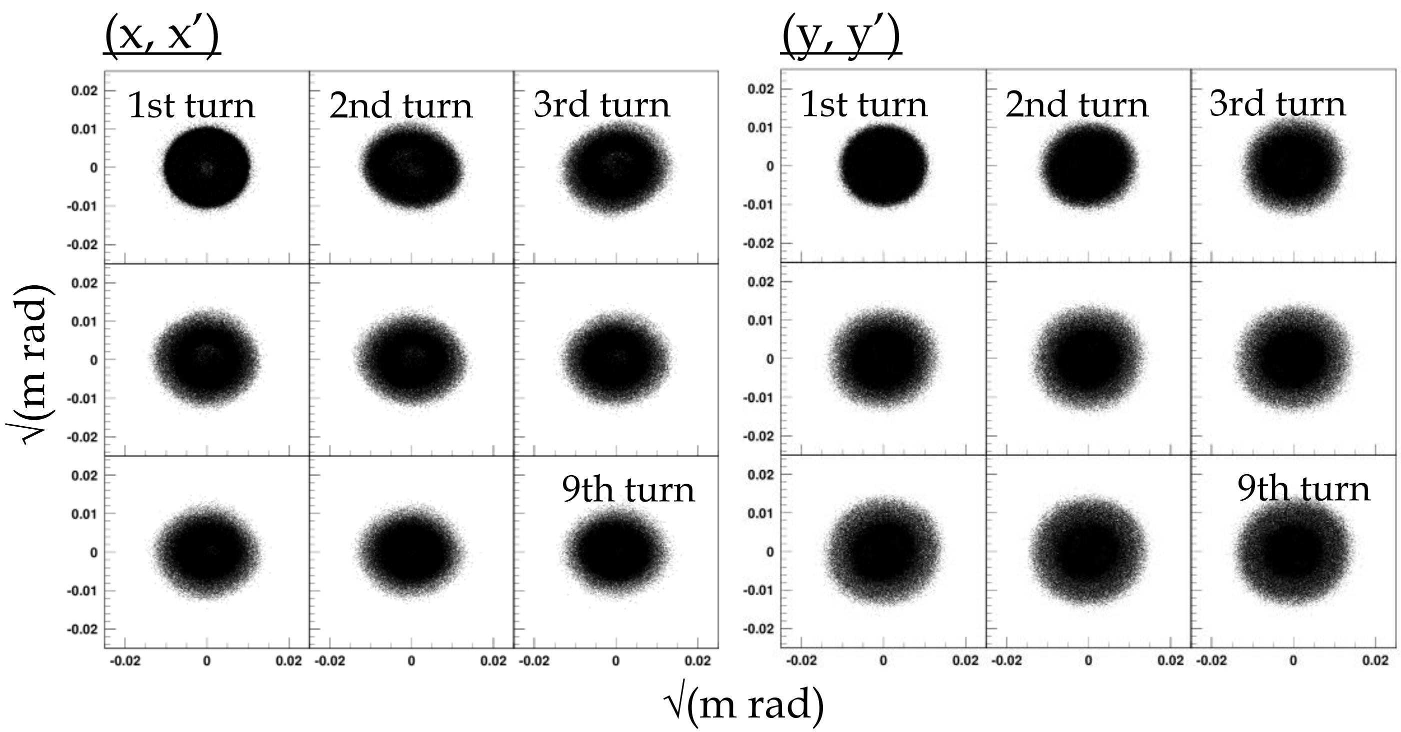
(y, y′)



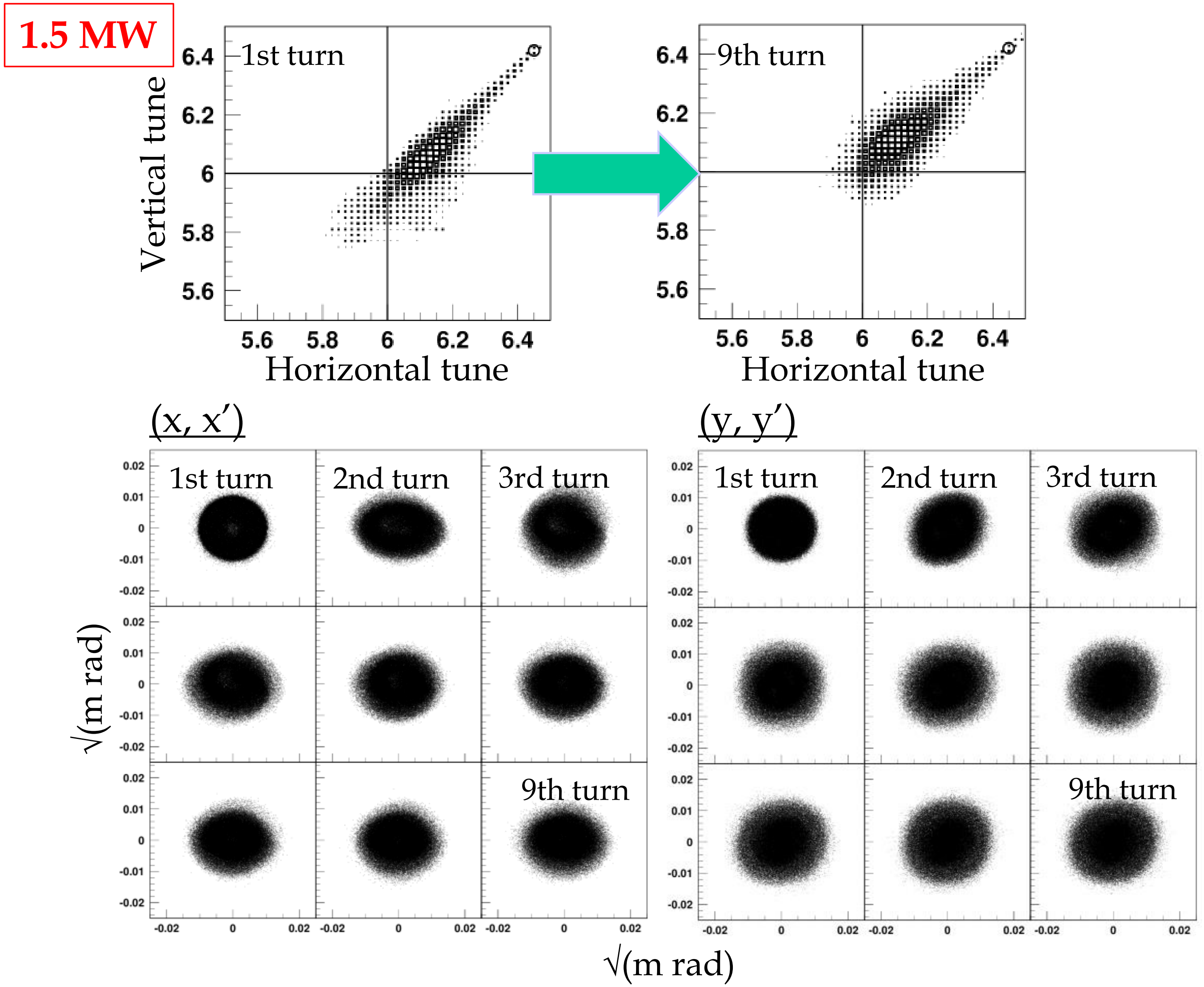
Evolution of the transverse phase space distribution

1.0 MW





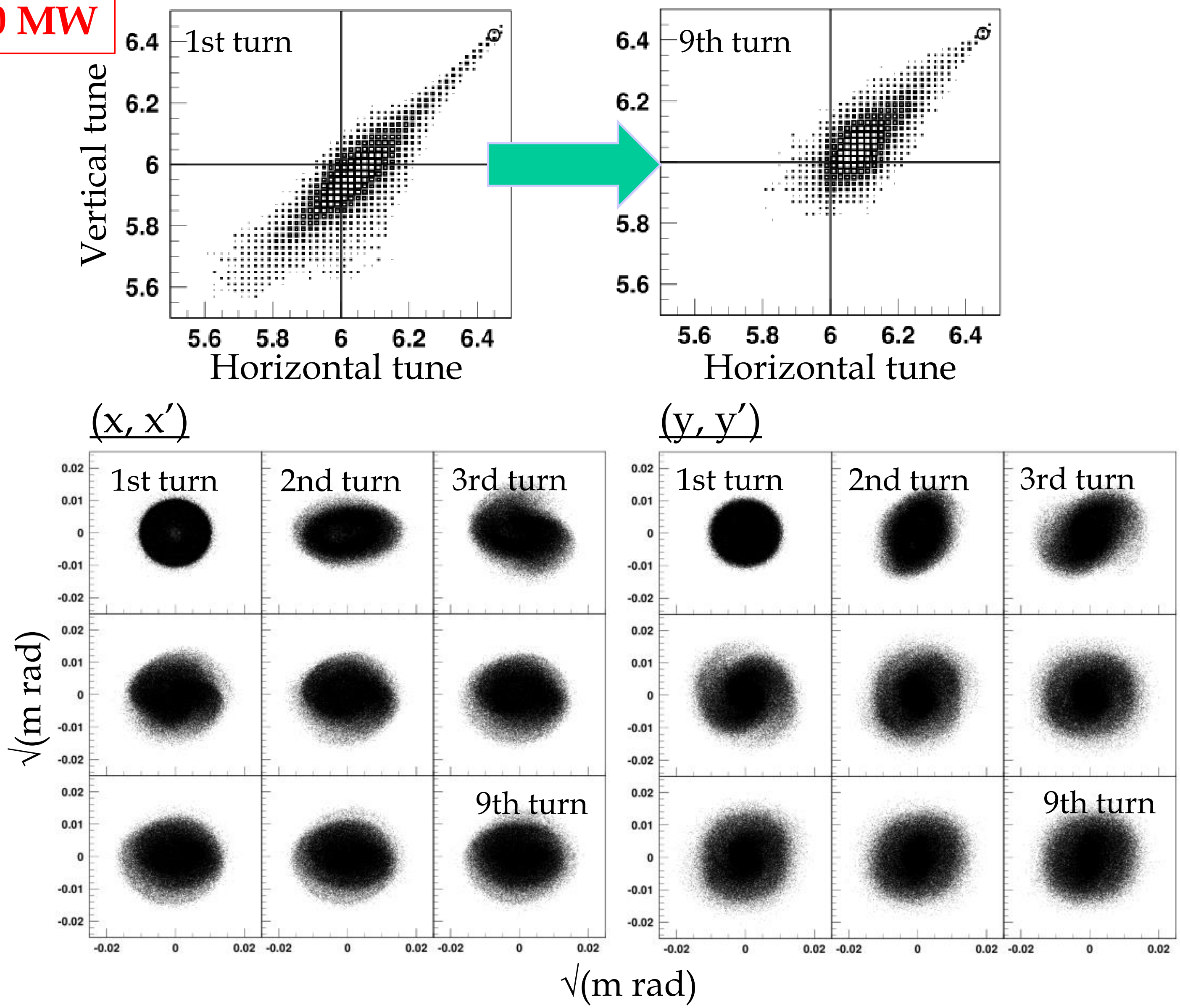
Evolution of the transverse phase space distribution



✓ The distribution is still stable.

Evolution of the transverse phase space distribution

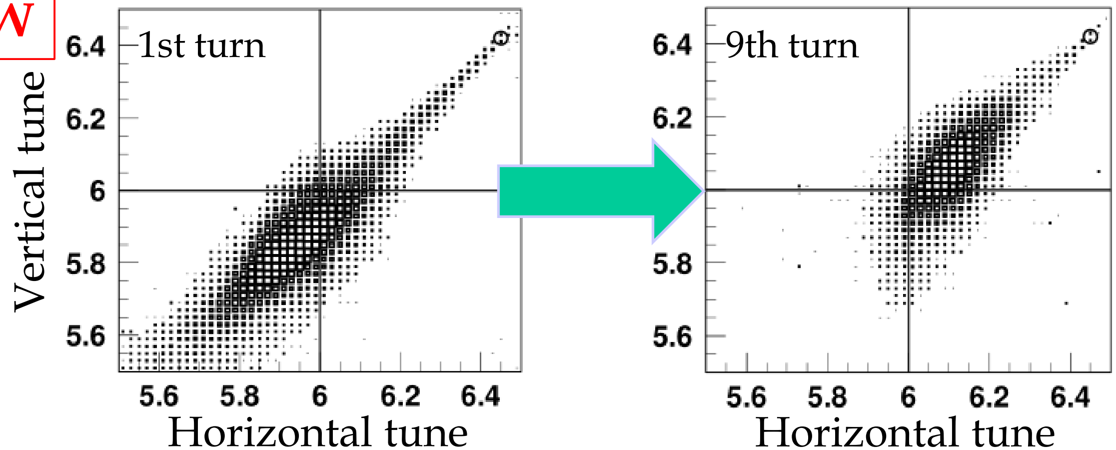
2.0 MW

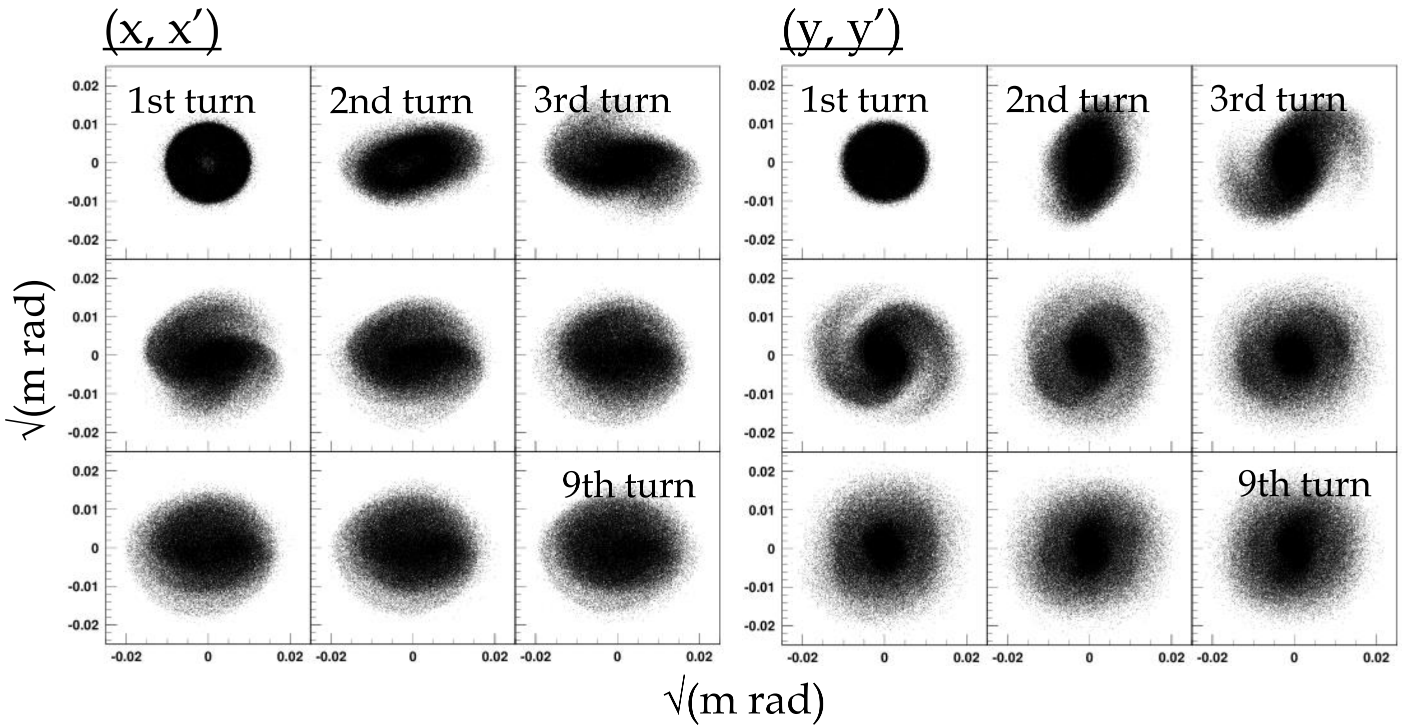


✓ Significant deformation of the beam distribution shows up.

Evolution of the transverse phase space distribution

2.5 MW

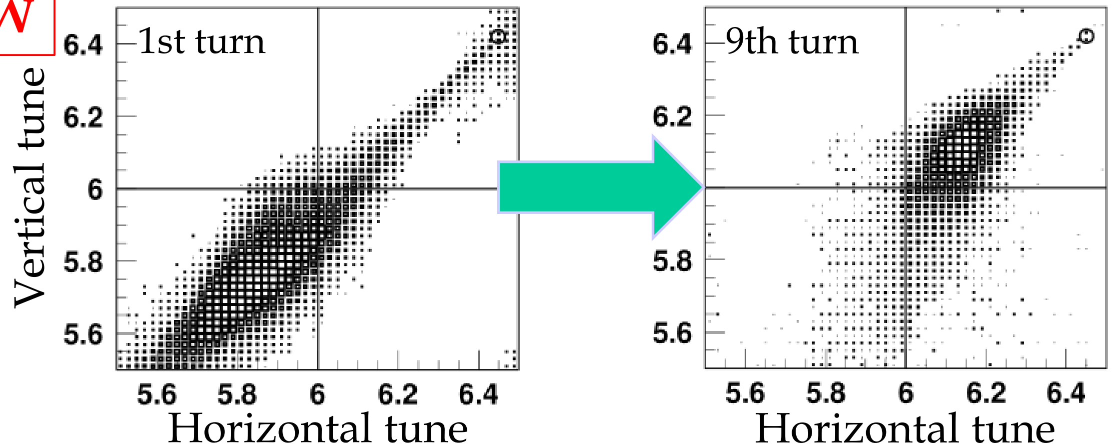


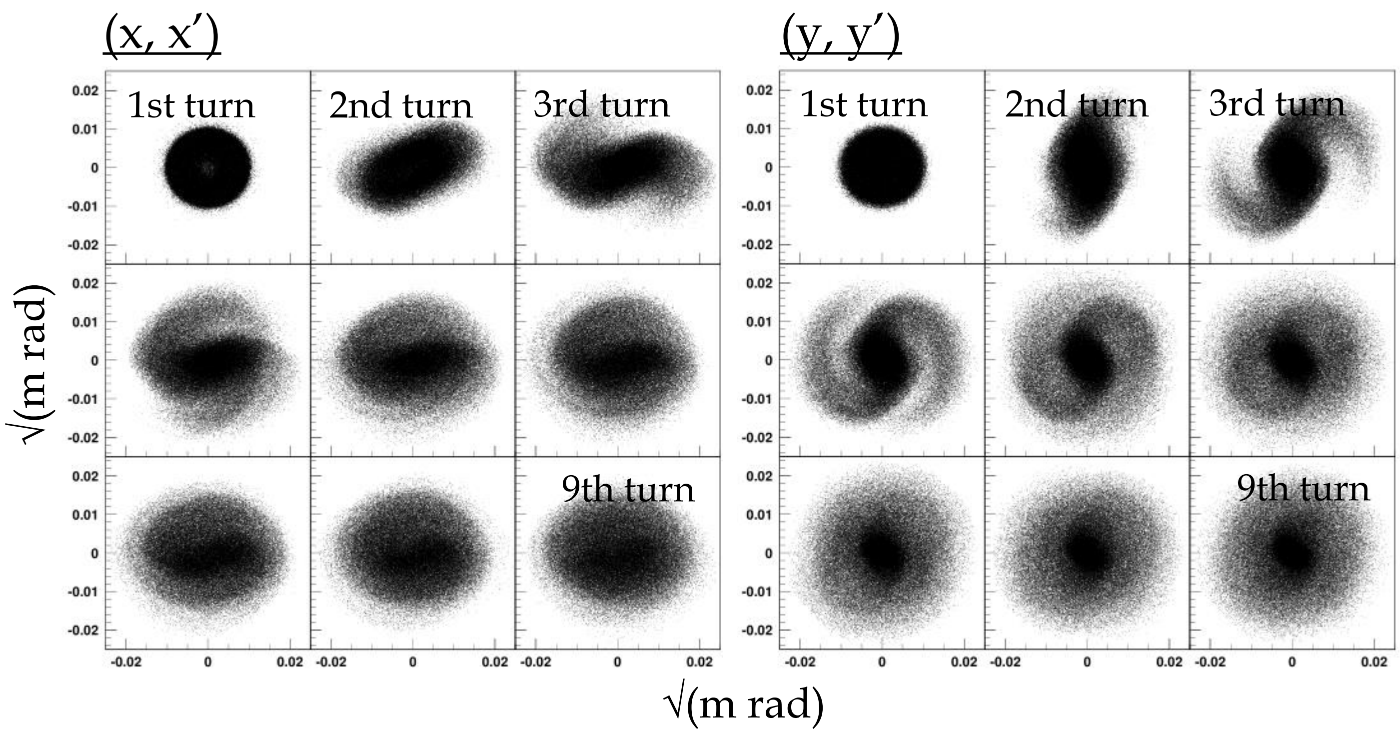


✓ The deformation is more enhanced.

Evolution of the transverse phase space distribution

3.0 MW





✓ The deformation is further enhanced.

Possible cause of the deformation of the beam distribution

✓ Coherent resonance ?

Resonant condition : $m(\nu_0 - C_m\Delta\nu) = n/2$

C_m : Coherent tune shift factor<1,
depending on the operational conditions,
initial distribution, etc.

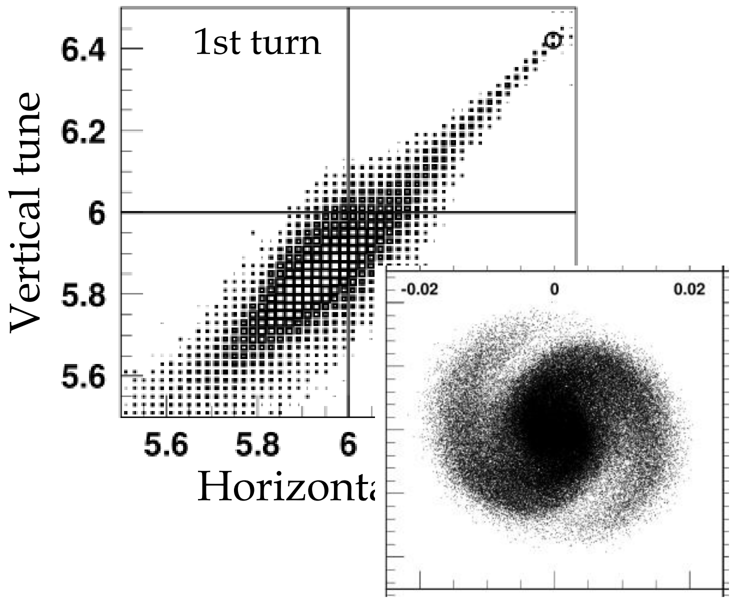
✓ The most probable cause of the deformation of the beam distribution observed after 2 MW-eq beam intensity is

2nd-order coherent structure resonance
$2(\nu_0 - C_2\Delta\nu) = 12$

existing around the integer.

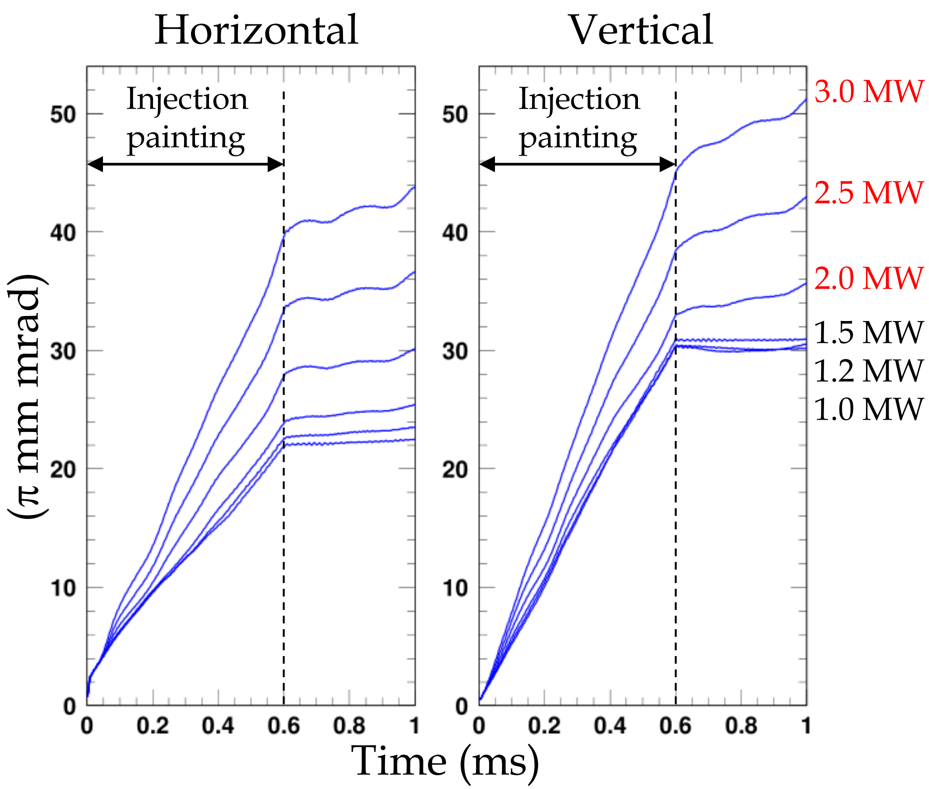
✓ It looks to show up when the rms tune shift reaches somewhat far below the integer depending on the C_2 factor.

2.5 MW



Possible cause of the emittance growth in the painting process

Normalized rms emittances obtained from the realistic simulations including the injection painting process



- ✓ Large emittance growths show up sharply after 2 MW-eq beam intensity also in the realistic simulations including the injection painting process.
- ✓ The 1-turn injection simulations imply that the emittance growths are caused by the 2nd-order coherent resonance.
- ✓ We have not yet found clear evidence for that in the realistic simulations.
  - Injection painting makes it difficult to confirm the resonance phenomenon.
  - The next subject in our study is to find the sign of the resonance in the complex injection painting process.

- ✓ The 2nd-order coherent resonance can be one of the important factors limiting the beam intensity achievable in the RCS.
- ✓ We will continue the study for that.

5. Summary

- We successfully demonstrated the 1-MW design beam operation with very low fractional beam loss of the order of 10^{-3}.
  - Most of the beam losses, that we encountered in the 1-MW beam tuning, were ascribed to incoherent betatron resonances; $3\nu_x=19$, $\nu_x+2\nu_y=19$, $\nu_x-2\nu_y=-6$, $2\nu_x-2\nu_y=0$, etc.
  - The beam losses were well reduced to the order of 10^{-3} by optimizing the operating point, injection painting, and by adding resonance corrections, etc.

- The success of the 1-MW beam operation opened a possibility of further beam power ramp-up beyond 1 MW.
  - We have recently performed 1.2-MW beam tests; the beam loss was successfully reduced to the order of 10^{-3}.
  - We will conduct a 1.5-MW beam test in Dec. 2019 with the improved RF system.

- We have recently performed beam simulations of up to 3 MW to explore the intensity limit of the RCS.
  - The simulations imply that the 2nd order coherent structure resonance, $2(\nu_0-C_2\Delta\nu)=12$, can be an important factor limiting the beam intensity.

Back-up slides

Numerical simulations

- **Code: Simpsons (developed by Shinji Machida)**
  - PIC,
  - 3-D motion of beam particles including space-charge and realistic injection process
- **Machine imperfections included:**
  - **Time independent imperfections**
    - Multipole field components for all the main magnets & the injection bump magnets:
      BM ($K_{1\sim6}$), QM ($K_{5,9}$), SM (K_8), and SB (K_2) obtained from field measurements
    - Measured field and alignment errors
  - **Time dependent imperfections**
    - Static leakage fields from the extraction beam line:
      $K_{0,1}$ and $SK_{0,1}$ estimated from measured COD and optical functions
    - Edge focus of the injection bump magnets:
      K_1 estimated from measured optical functions
    - BM-QM field tracking errors
      estimated from measured tune variation over acceleration
    - 1-kHz BM ripple
      estimated from measured orbit variation
    - 100-kHz ripple induced by injection bump magnets
      estimated from turn-by-turn BPM data . . . etc.
  - **Foil scattering:**
    Coulomb & nuclear scattering angle distribution calculated with GEANT

✓ Now the numerical simulation well reproduces the experimental results, and plays a vital role in solving beam loss issues in the RCS.

Transverse injection painting

- Horizontal painting by a
  horizontal closed orbit variation
  during injection

  The injection beam is filled
  - (a) from the middle to the outside

  on the horizontal phase space.

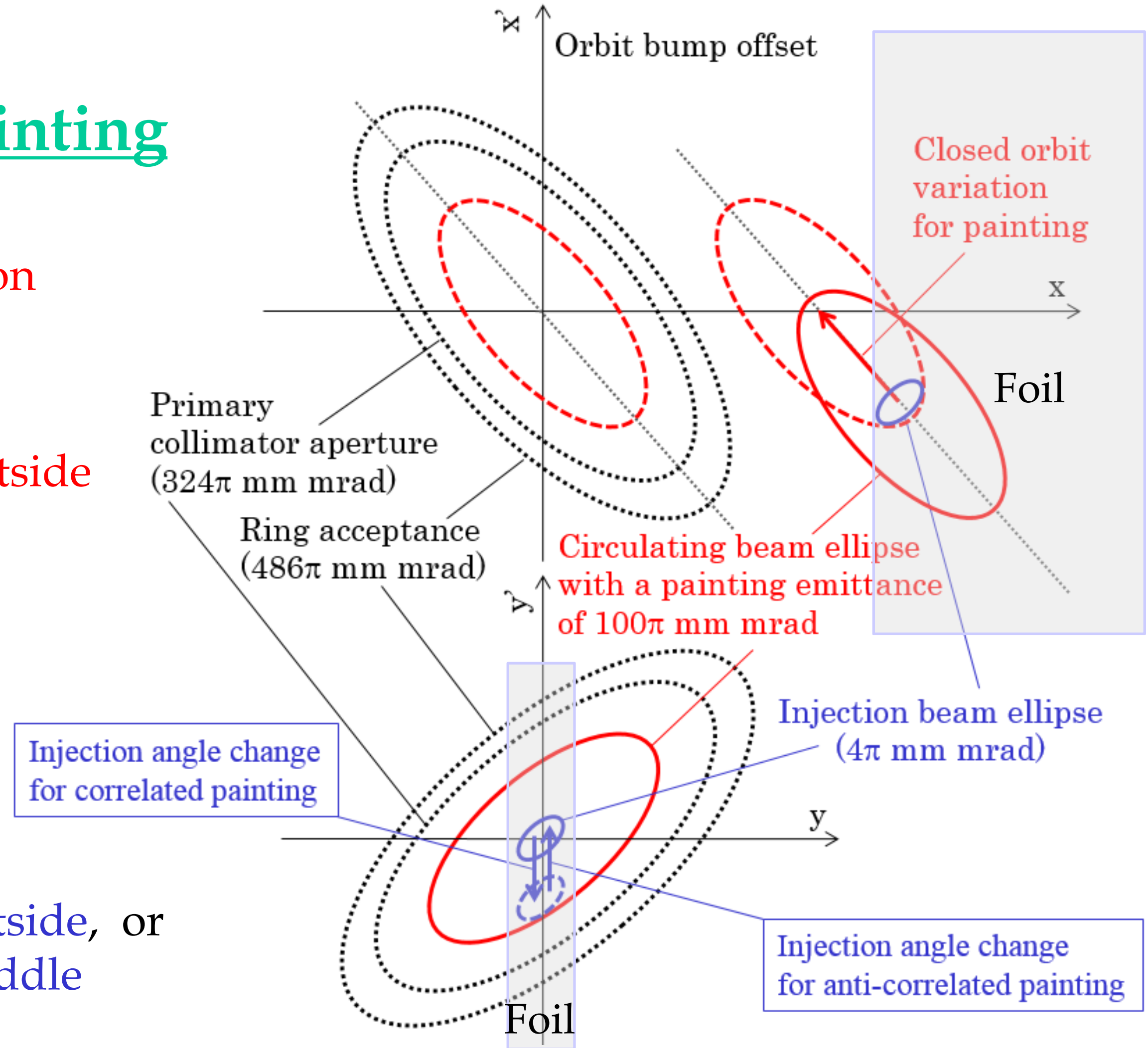
- Vertical painting by a
  vertical injection angle change
  during injection

  The injection beam is filled
  - (b) from the middle to the outside, or
  - (c) from the outside to the middle

  on the vertical phase space.

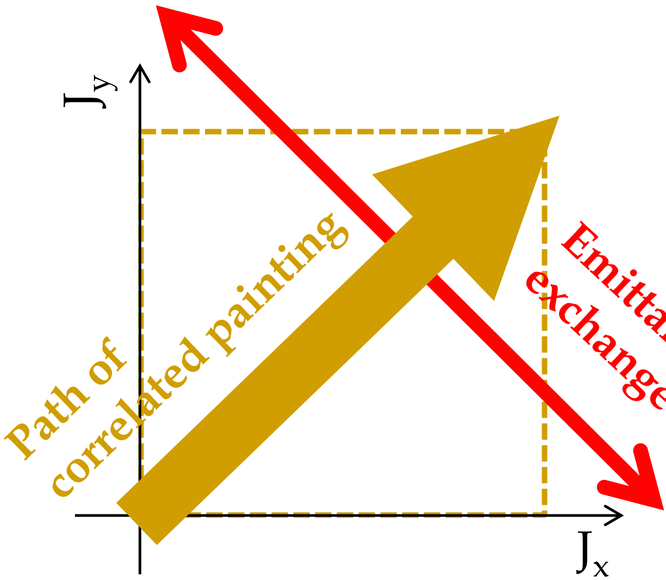
(a)+(b) ⇒ Correlated painting
(a)+(c) ⇒ Anti-correlated painting

Painting emittance; ε_{tp}=0~216π mm mrad

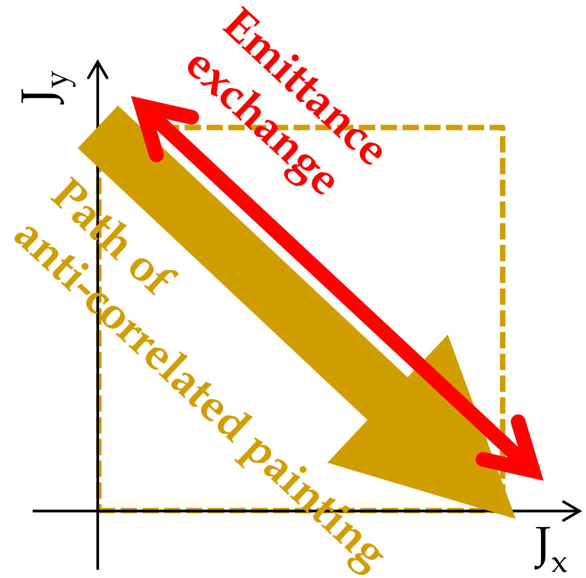


Correlated painting vs anti-correlated painting

Correlated painting of ε_{tp}=200π mm mrad



Anti-correlated painting of ε_{tp}=200π mm mrad



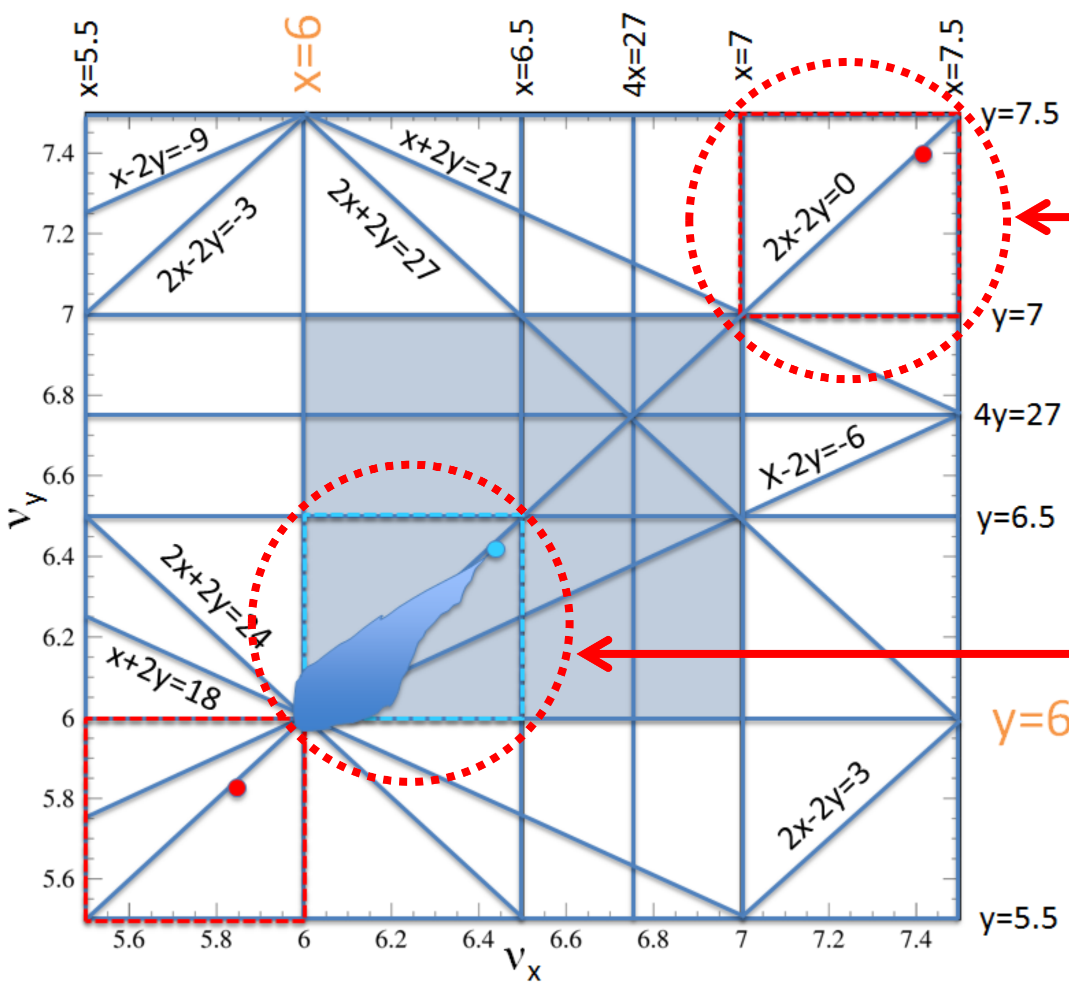
✓ The emittance exchange occurs perpendicularly to the path of beam painting.

⇒ This causes large emittance diffusion.

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

⇒ This geometrical situation well prevents the emittance exchange from causing emittance diffusion.

Tune diagram



- ✓ Near ν=7, possible orders of systematic resonances are very restricted.
  - m=3, 6, 9 ･･･
  - This region above ν=7 can be more suitable for higher beam intensities.
- ✓ Near ν=6, all order systematic resonances can be excited.
  - m=2, 3, 4, 5, 6 ･･･
  - Very strong stopbands exist.