# The Path to 1 MW
# Beam Loss Control in the J-PARC 3-GeV RCS

## HB2016

**Malmö, Sweden, 3-8 July 2016**

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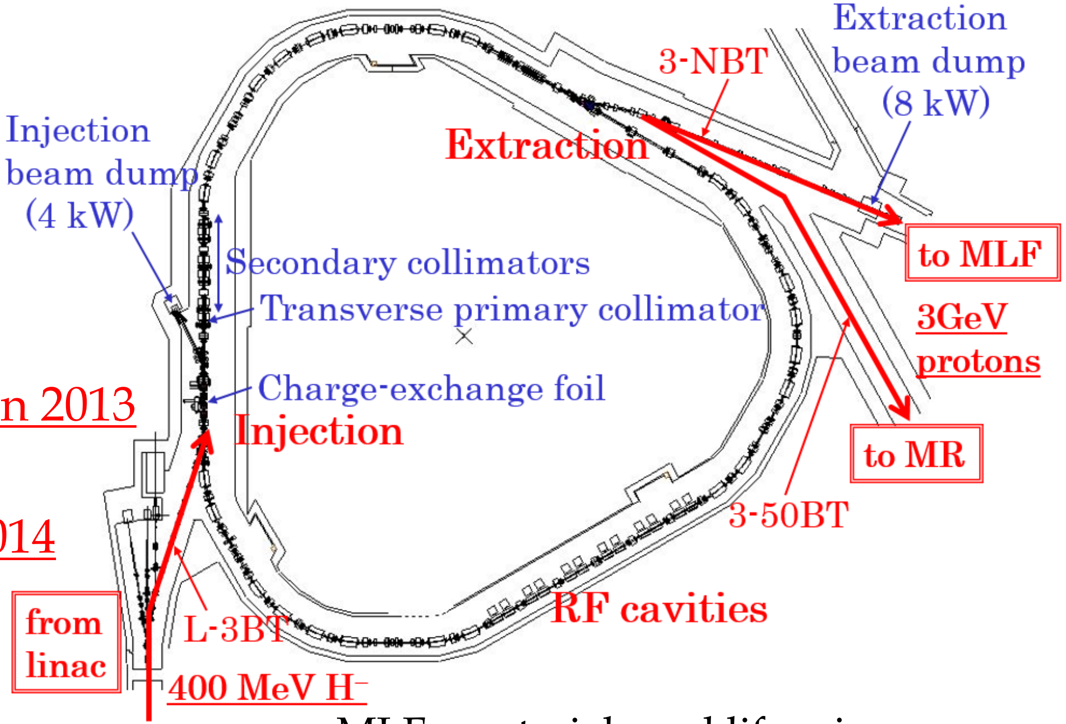
# Outline of the J-PARC 3-GeV RCS

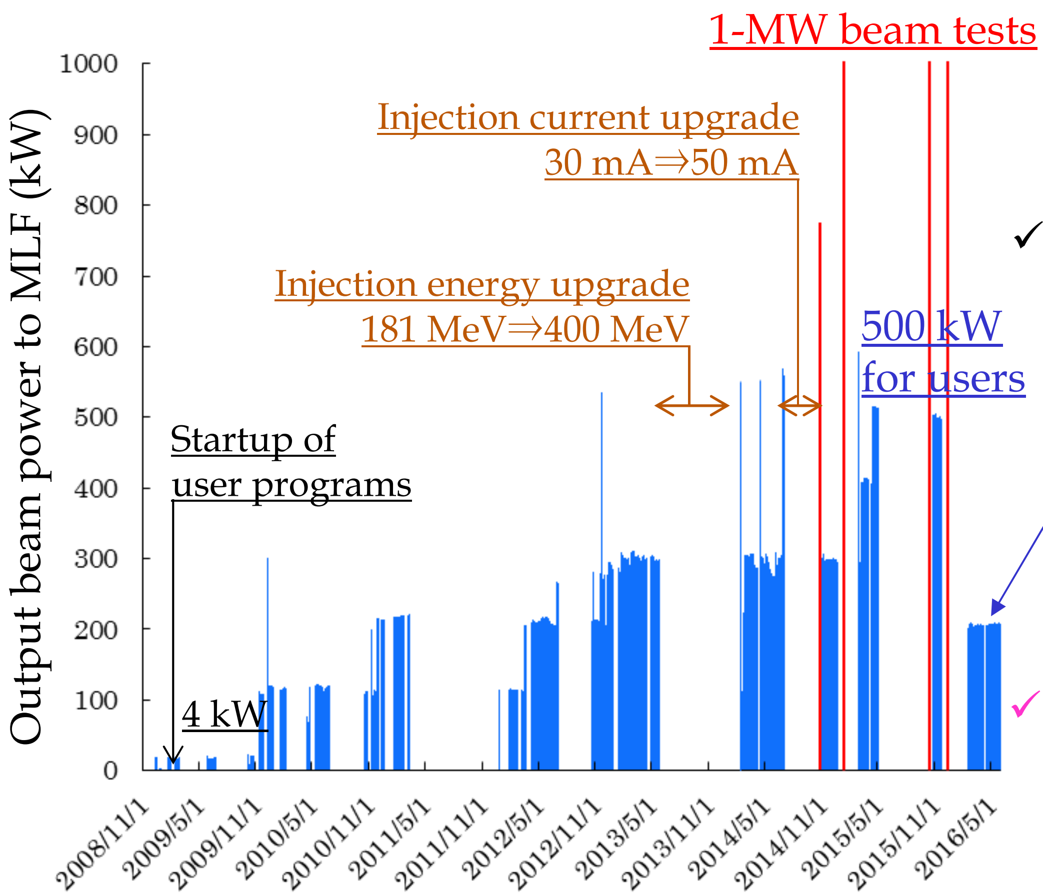
| | |
|---|---|
| Circumference | 348.333 m |
| Superperiodicity | 3 |
| Harmonic number | 2 |
| Number of bunches | 2 |
| Injection | Multi-turn, Charge-exchange |
| Injection energy | 181 MeV ⇒ 400 MeV in 2013 |
| Injection period | 0.5 ms (307 turns) |
| Injection peak current | 30 mA ⇒ 50 mA in 2014 |
| Extraction energy | 3 GeV |
| Repetition rate | 25 Hz |
| Particles per pulse | $5 \times 10^{13}$ ⇒ $8.3 \times 10^{13}$ |
| Output beam power | 600 kW ⇒ 1 MW |
| Transition gamma | 9.14 GeV |
| Number of dipoles | 24 |
| quadrupoles | 60 (7 families) |
| sextupoles | 18 (3 families) |
| steerings | 52 |
| RF cavities | 12 |




MLF : materials and life science experimental facility
MR : 50-GeV main ring synchrotron

- ✓ Recently the hardware improvement of the injector linac was completed.
- ✓ RCS is now in the final beam commissioning phase aiming for the design output beam power of 1 MW.

# History of the RCS beam power




- ✓ The RCS output beam power has been steadily increasing following progressions in beam tuning and hardware improvements.
- ✓ The output beam power for the routine user program has been increased to 500 kW to date.

*** The beam power is now temporarily limited to 200 kW due to a malfunction of the neutron production target at MLF.

- ✓ We started the 1-MW beam test in October 2014 and successfully achieved a 1-MW beam acceleration in January 2015.

In realizing such a MW-class high-power routine beam operation, beam loss is a key issue.
A large fraction of our effort has been focused on reducing and managing beam loss.

# Contents of my talk

◆ Recent progresses of 1-MW beam tuning

◆ Approaches to beam loss issues

**1. Results of the first stage of the 1-MW beam test**

- Longitudinal beam loss and its mitigation
- Transverse beam and its localization
- Beam instability and its suppression

**2. Further beam loss mitigation by larger transverse painting**

- Realizing 150π-mm-mrad transverse painting
- Realizing 200π-mm-mrad transverse painting

**3. Summary**

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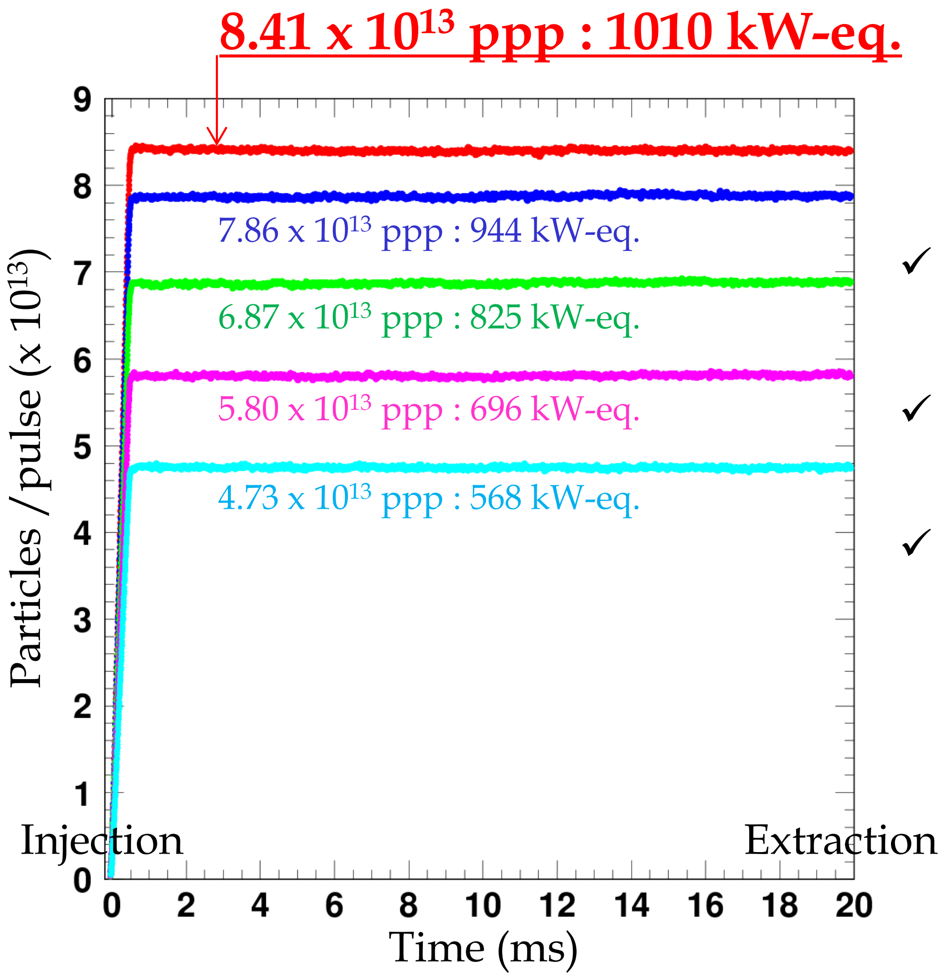
# Achievement of the 1-MW beam acceleration

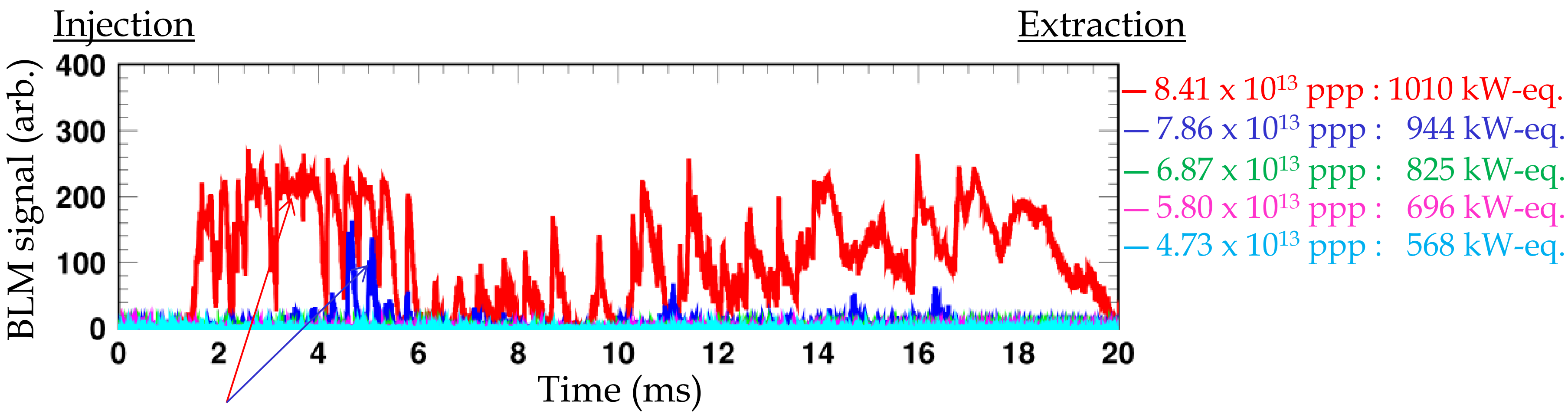
Circulating beam intensity over the 20 ms
from injection to extraction measured by CT




- ✓ RCS successfully achieved the 1-MW beam acceleration in January 10, 2015.
- ✓ There was no significant beam loss even for the 1-MW beam.
- ✓ But, at this stage, there still remained slight un-localized beam loss ($<10^{-3}$) in the high dispersion area.

# Longitudinal beam loss and its mitigation

BLM signals in the high dispersion area at the arc sections




✓ Longitudinal beam loss arising from a RF bucket distortion caused by beam loading.

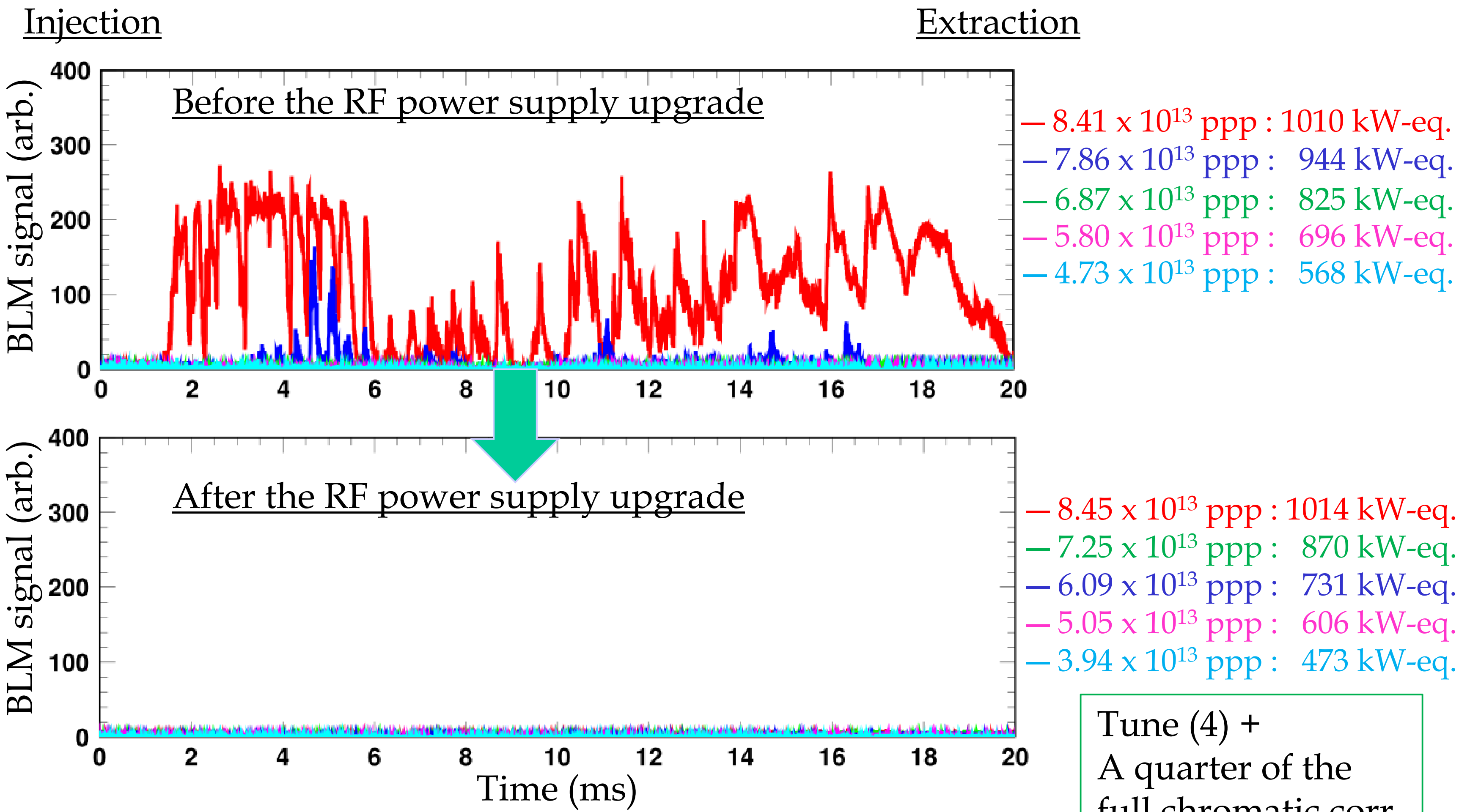
- In RCS, a multi-harmonic feed-forward system is employed for beam loading compensation and it works very well.
- But, at this stage, the RF power supply nearly reached the limit, and there was no enough margin for sufficient beam loading compensation for the 1-MW beam.
- The limitation of the RF power supply is the fundamental cause of this beam loss.

✓ RF power supply upgrade in the 2015 summer maintenance period

✓ 1-MW beam test again in October 2015

# Longitudinal beam loss and its mitigation

BLM signals in the high dispersion area at the arc sections



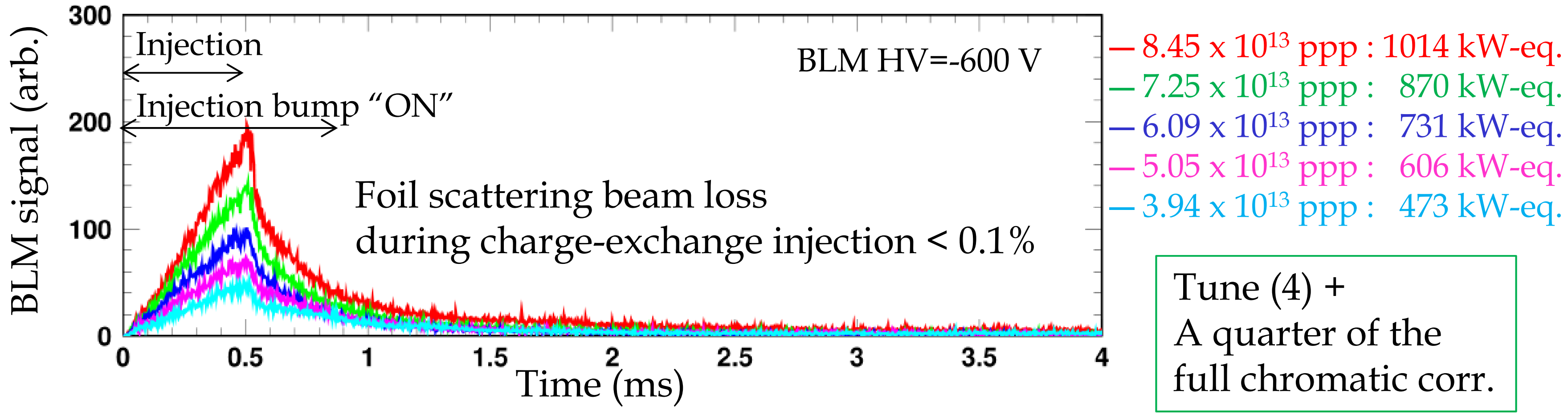

Tune (4) +
A quarter of the
full chromatic corr.

✓ Longitudinal beam loss was completely removed by beam loading compensation conducted after the RF power supply upgrade.

# Transverse beam loss and its localization

✓ Most of transverse beam loss was well localized at the collimator in the dispersion-free long straight insertion.

BLM signals at the collimator




Tune (4) +
A quarter of the
full chromatic corr.

✓ The beam loss at the collimator appears only for the first 1 ms of beam injection, and its amount simply shows a linear beam intensity dependence.
⇒ The beam loss mainly arises from foil scattering during charge-exchange injection.

✓ The other beam loss, such as space-charge induced beam loss, was well minimized by injection painting even for the 1-MW beam.

✓ The beam loss for the 1-MW beam was estimated to be
< 0.1% (< 133 W in power) << Collimator limit of 4 kW.

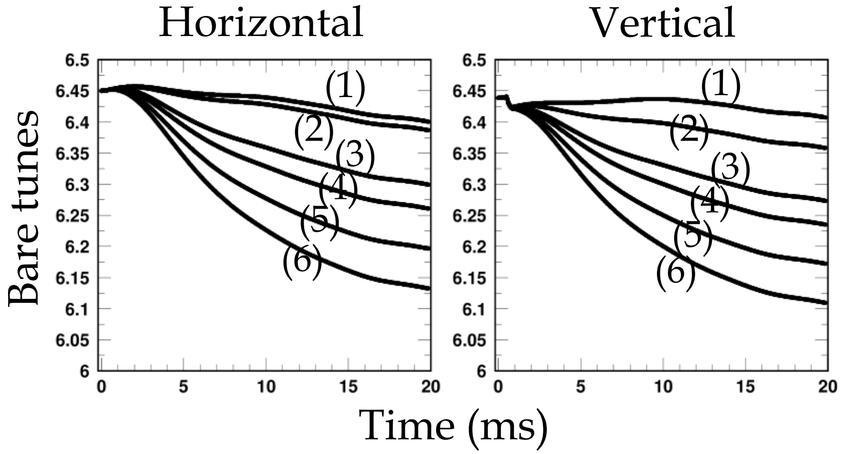
# Beam instability and its suppression

- ✓ The extraction pulse kicker is the most dominant impedance source, causing horizontal beam instability depending on the choice of the operational parameters.
- ✓ For its suppression, the systematic beam instability measurement was done with different tunes and chromaticities at the initial stage of the 1-MW beam test.

- 1 MW, (6.45, 6.42) @ inj.
- w/ 100π-mm-mrad-correlated painting
- w/ longitudinal painting

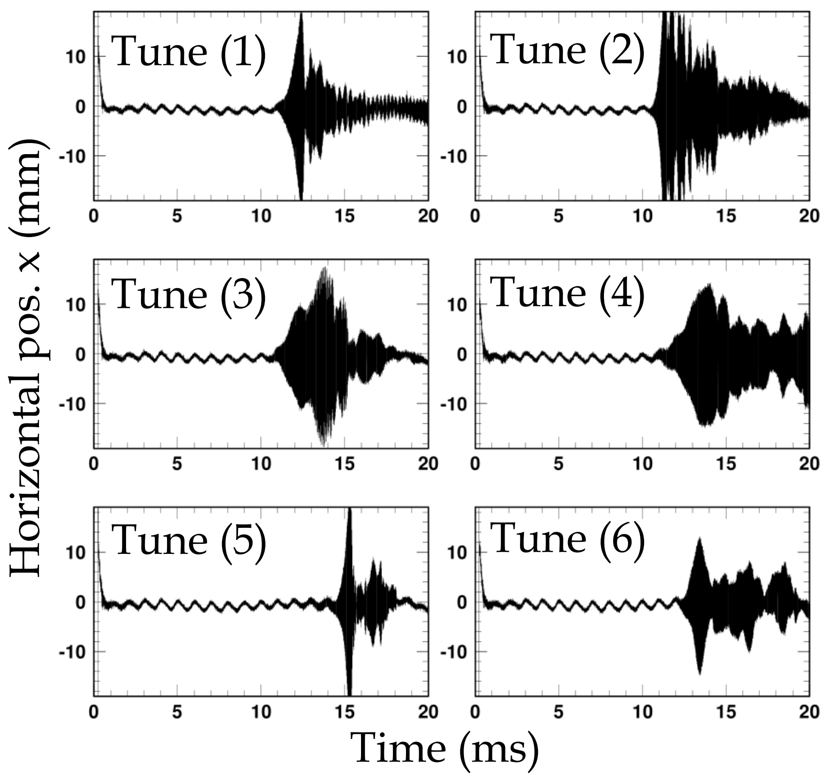
◆ Chromaticity correction:
the chromaticity was fully corrected to ~0 at injection with dc sextupole field.

Tune variation during acceleration




- ✓ Beam instability occurred for any choice of tune variation.
- ✓ But this situation drastically changes by reducing the degree of the chromaticity correction.

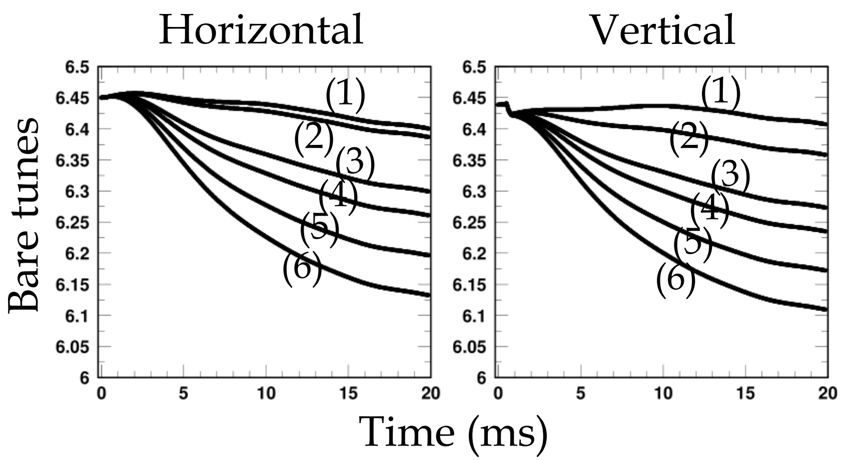
Turn-by-turn horizontal beam position



# Beam instability and its suppression

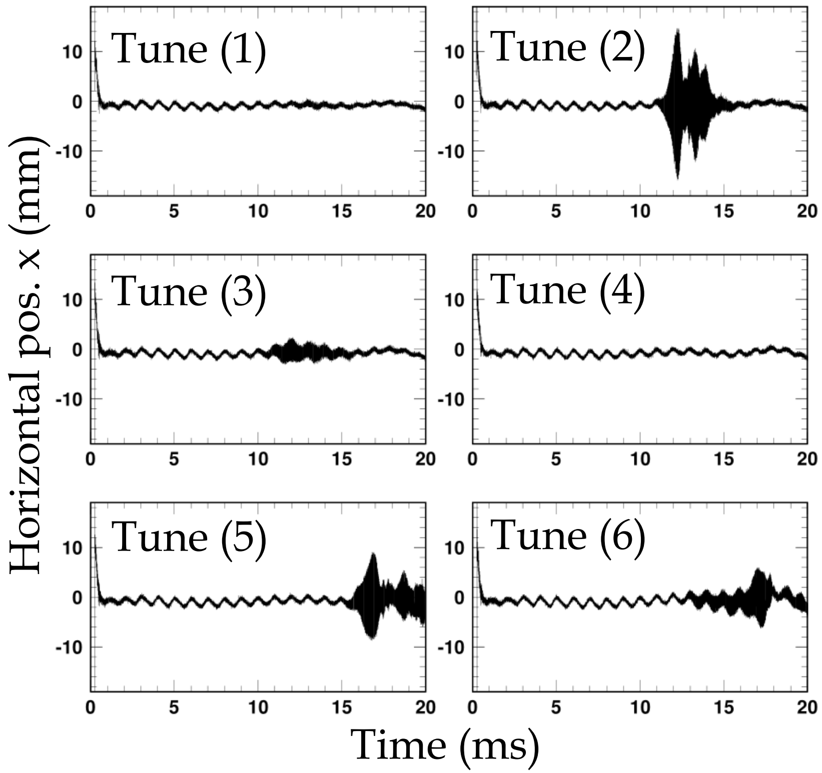
- 1 MW, (6.45, 6.42) @ inj.
- w/ 100π-mm-mrad correlated painting
- w/ longitudinal painting

Tune variation during acceleration




◆ Chromaticity correction:
only a quarter of the natural chromaticity was corrected at injection with dc sextupole field.

Turn-by-turn horizontal beam position

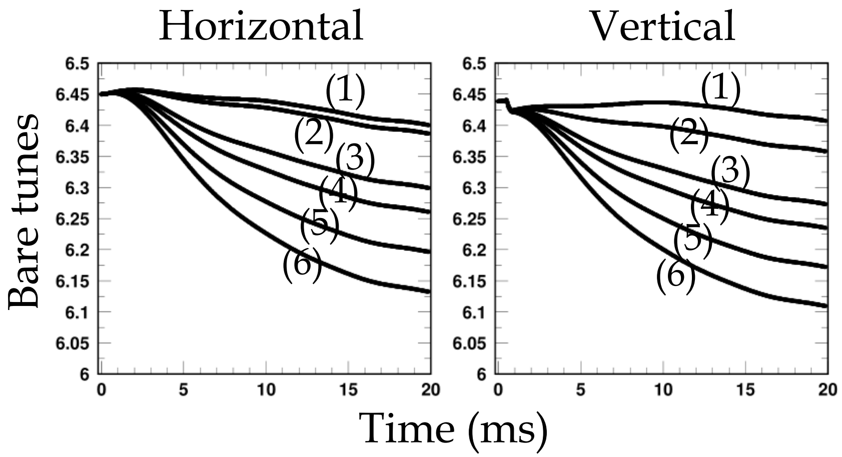


# Beam instability and its suppression

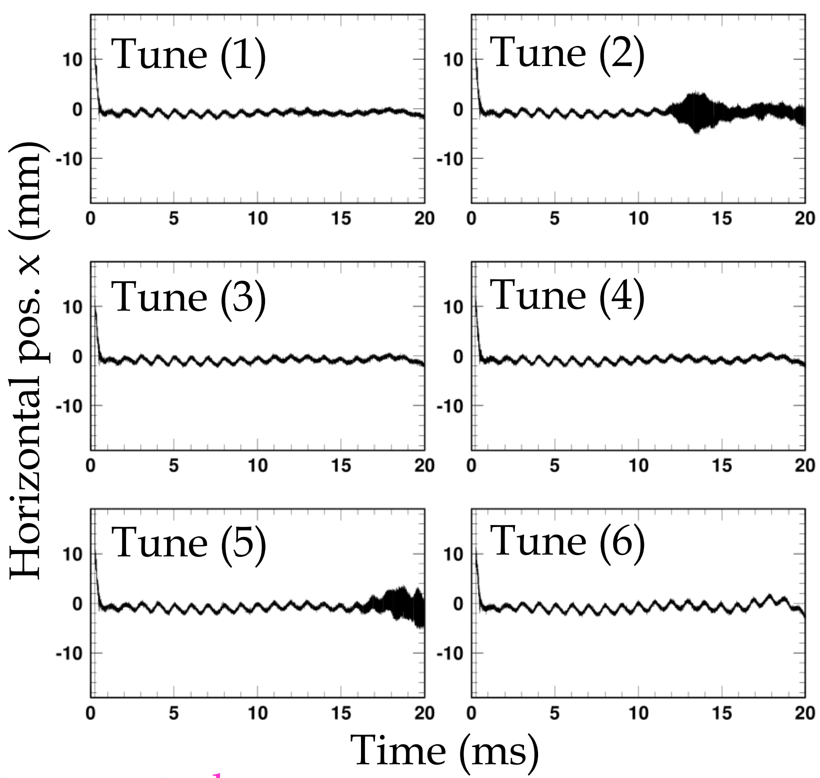
- 1 MW, (6.45, 6.42) @ inj.
- w/ 100π-mm-mrad correlated painting
- w/ longitudinal painting

◆ Chromaticity correction: not applied

Tune variation during acceleration




Turn-by-turn horizontal beam position




✓ The beam instability is more stabilized by Landau damping through momentum spread as the negative chromaticity becomes larger.

✓ The situation with less chromaticity correction enables us to fully damp the beam instability in combination with tune control.

✓ Though this measurement, the operational condition to damp the beam instability was clearly revealed.

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2. **Further beam loss mitigation by larger transverse painting**
   - Realizing 150π-mm-mrad transverse painting
   - Realizing 200π-mm-mrad transverse painting

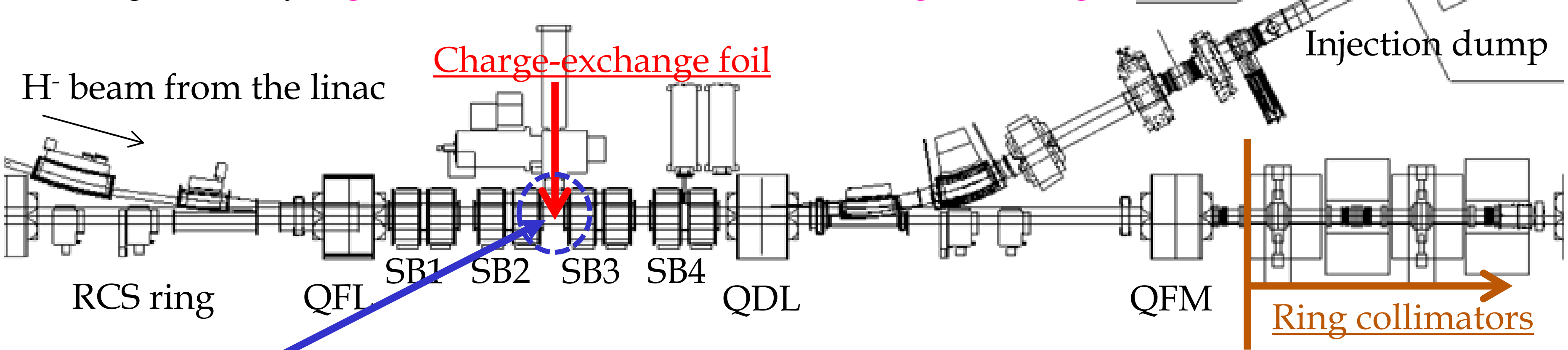
3. **Summary**

# Further beam loss mitigation by larger transverse painting

Beam loss other than foil scattering beam loss was well minimized at the initial stage of the 1-MW beam test.

✓ The next subject in our beam study was to further reduce the foil scattering beam loss.

Most of the foil scattering beam loss is well localized at the collimators, but some of them with large scattering angles cause un-localized beam loss, making relatively high machine activation near the charge-exchange foil.




~15 mSv/h on the chamber surface right after the 400-kW routine beam operation

⇒ ~38 mSv/h if the output beam power is increased to 1 MW as is

✓ This radiation level is still considered to be within the acceptable level, but it has to be further reduced to preserve a better hands-on-maintenance environment.

The amount of the foil scattering beam loss is in proportion to the foil hitting rate during charge-exchange injection.

✓ One possible solution to reduce the foil hitting rate is to expand the transverse painting area.

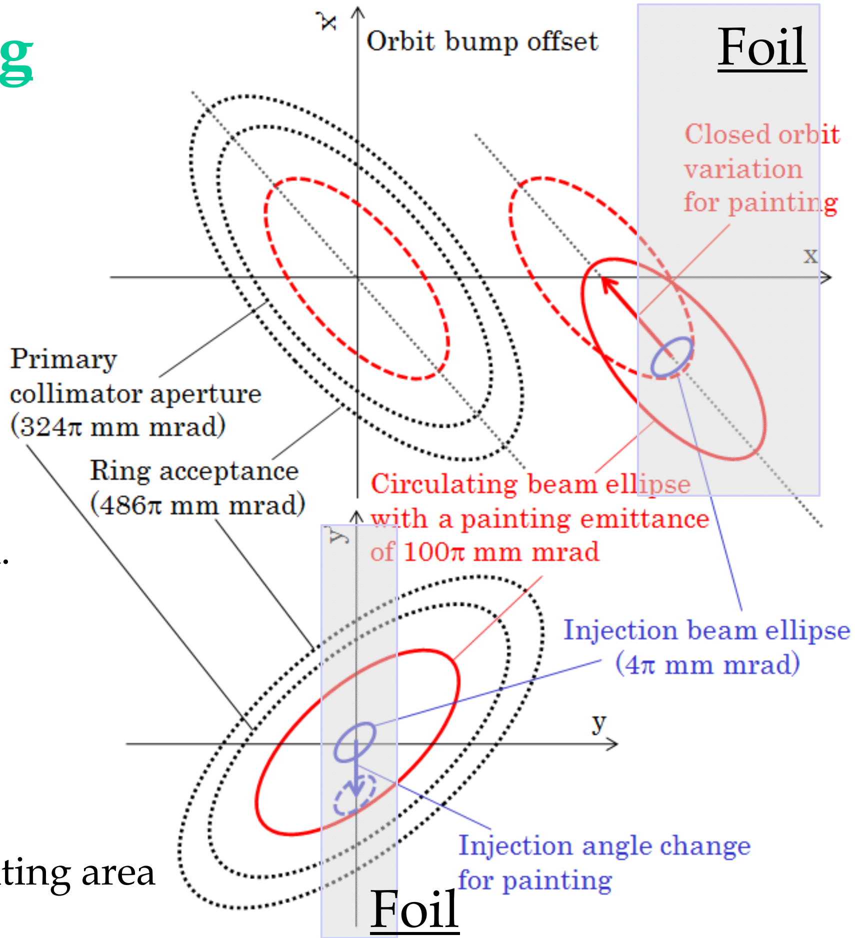
# Transverse injection painting

- Horizontal painting
  by a horizontal closed orbit variation during injection

  The foil hitting rate decreases
  as the horizontal painting area
  becomes wider, because
  the circulating beam more rapidly
  escapes from the foil thanks to
  the larger horizontal closed orbit variation.

- Vertical painting
  by a vertical injection angle change during injection

  Vertical painting also acts to reduce
  the foil hitting rate through the wider painting area
  than the vertical dimension of the foil.



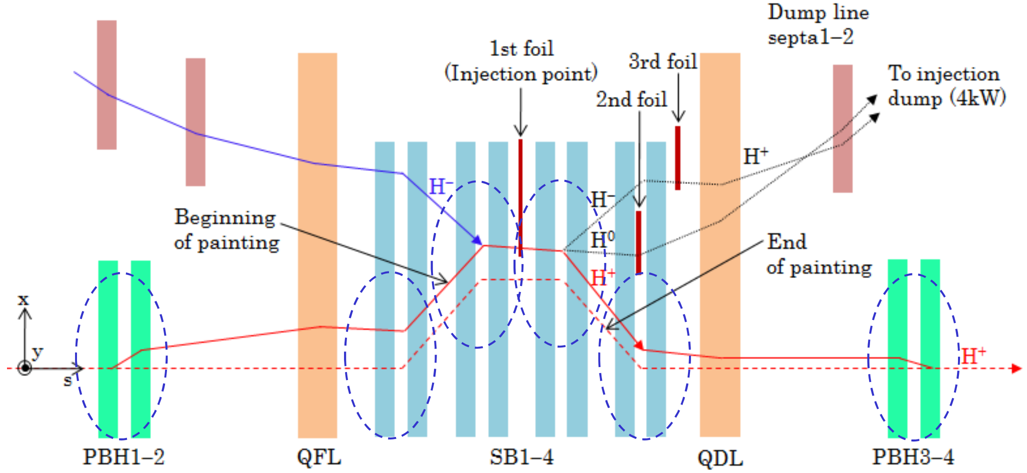

| Painting area (π mm mrad) | Averaged number of foil-hits per particle |
|---|---|
| 100 | 41 |
| 150 | 25 |
| 200 | 15 |

✓ The foil scattering beam loss can be reduced by larger transverse painting.

✓ But such a large transverse painting had not been realized until recently due to beta function beating caused by the edge focus of the injection bump magnets.

# Beta function beating caused by injection bump magnets

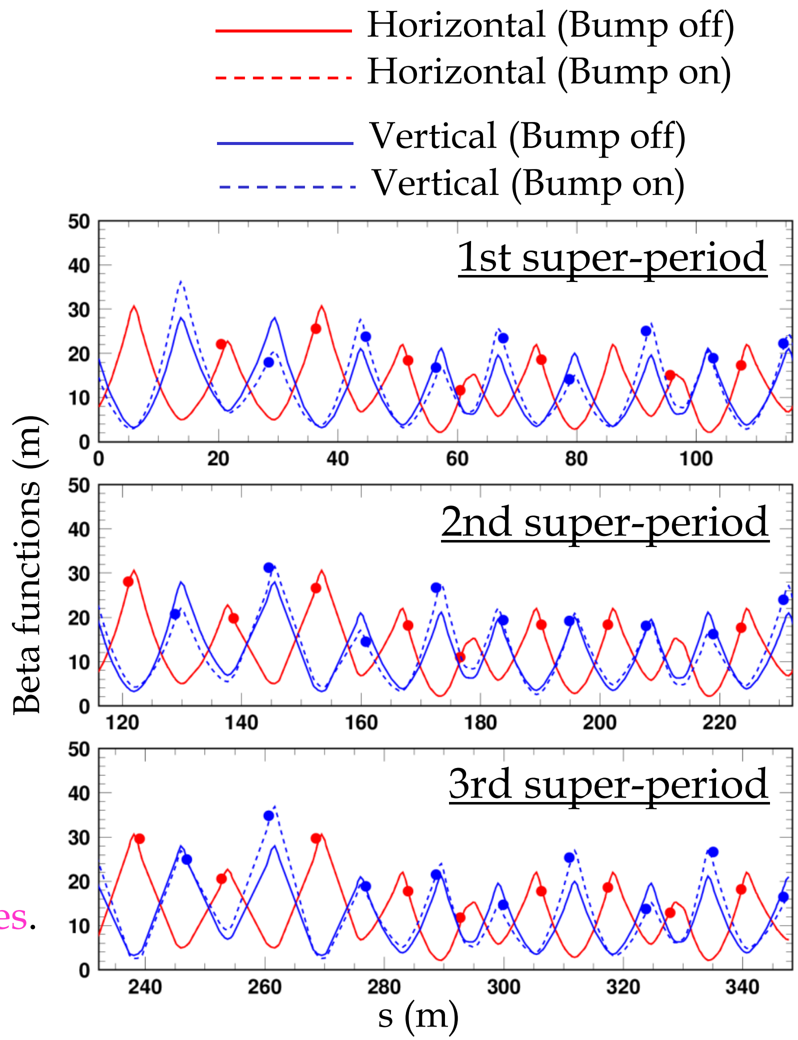
- ✓ Beam injection is performed with a time dependent horizontal local bump orbit by using 8 sets of rectangular pulse dipoles magnets (SB1-4 & PBH1-4 ).




- ✓ This way generates edge focus at the entrance and exit of the injection bump magnets.

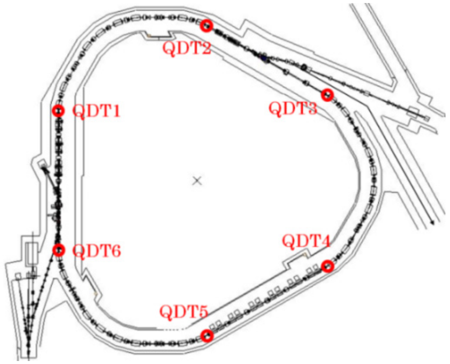
- ✓ The edge focus causes a 30% big beta function beating on the vertical plane during injection.
- ✓ The beta function beating makes a distortion of the lattice super-periodicity and additionally excites various random betatron resonances.
- ✓ Such random resonances cause an additional shrinkage of the dynamic aperture during the injection period, leading to extra beam loss when the transverse painting area is enlarged.

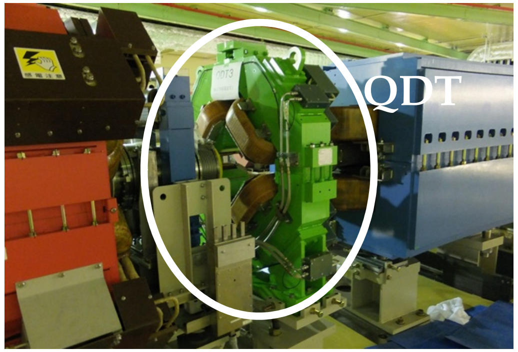
Beta function beating caused by edge focus of the injection bump magnets



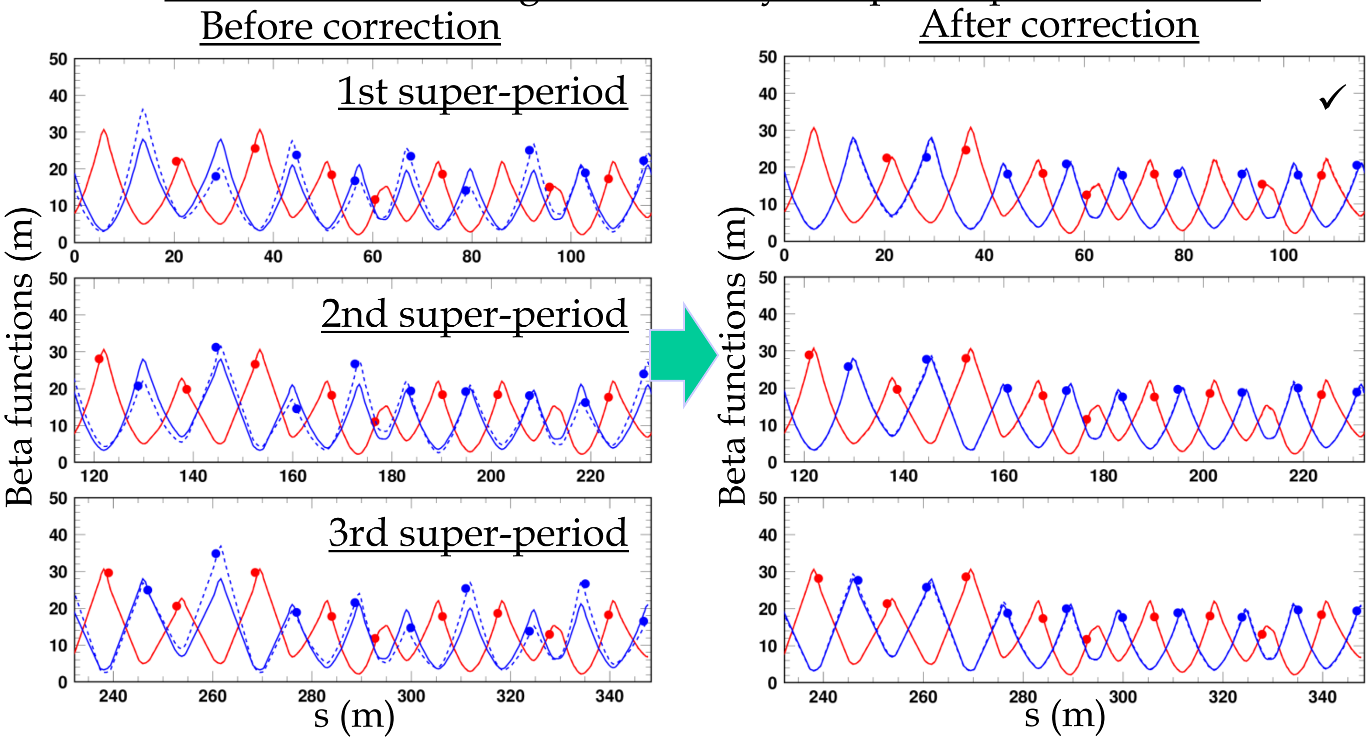
# Correction of beta function beating

- ✓ Six sets of pulse type quadrupole correctors (QDTs) were recently installed to compensate the beta function beating, by which the effect of the random resonances can be minimized through the recovery of the super-periodic condition.




Beta function beating correction by the quadrupole correctors.



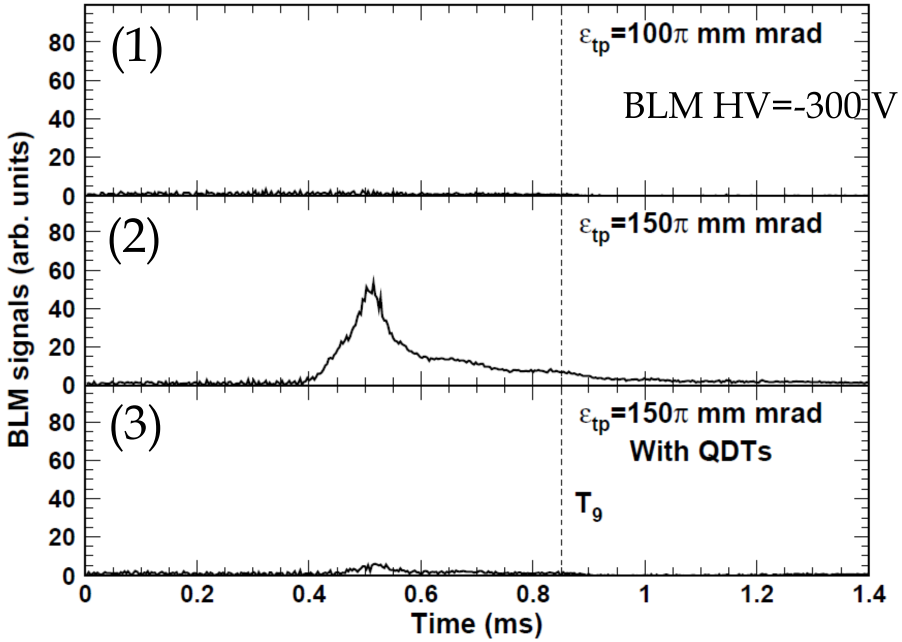

✓ Vertical beta function beating was well corrected by QDTs, while keeping the super-periodic condition on the horizontal plane.

# Realizing 150π-mm-mrad transverse painting

Experimental condition

- Injection beam condition
  - Injection energy : 400 MeV
  - Peak current : 37.6 mA
    - @ the entrance of RCS
  - Pulse length : 0.5 ms
  - Chopper beam-on duty factor : 60%
  - ⇒ $7.06 \times 10^{13}$ particles/pulse,
  - corresponding to 847 kW at 3 GeV
- Operating point;
  - (6.45, 6.38)

BLM signals at the collimator




(1) No significant beam loss, for the case of the transverse painting area of 100π mm mrad.

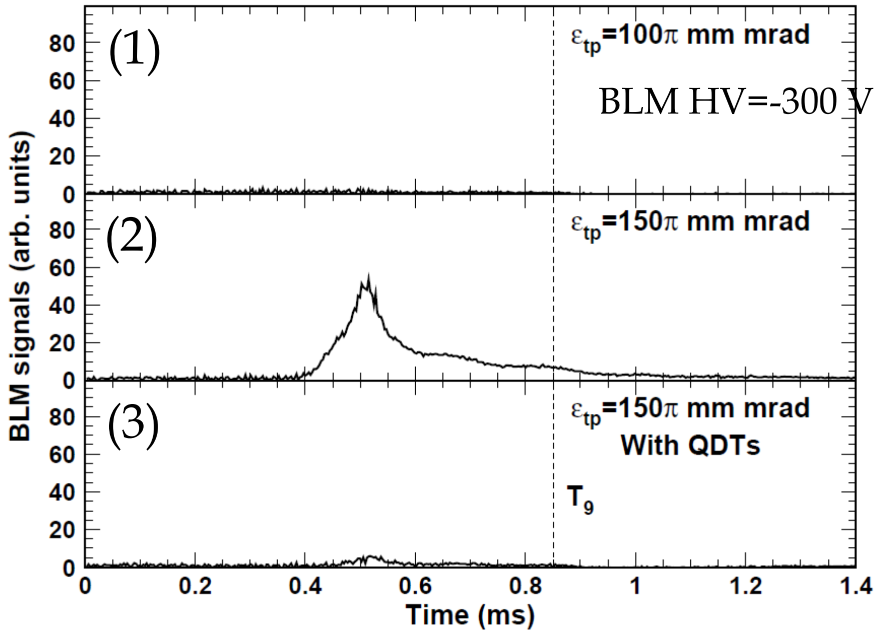
(2) When expanding the transverse painting area to 150π mm mrad, significant extra beam loss appeared.

(3) The extra beam loss was well minimized as expected with QDTs.

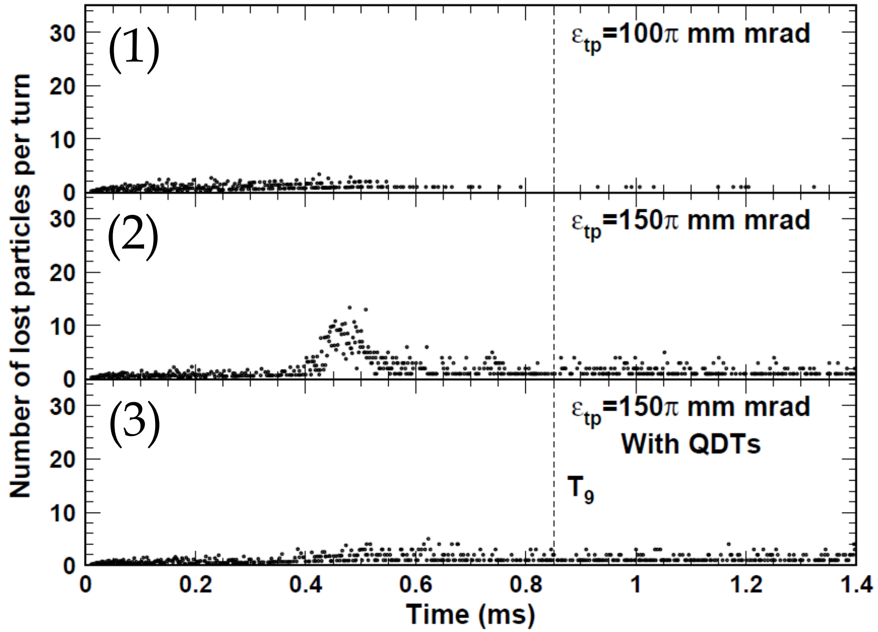
✓ The transverse painting area was successfully enlarged to 150π mm mrad with no significant extra beam loss by introducing QDTs.

# Measurement vs Numerical simulation

Measurement ;
BLM signals at the collimator section



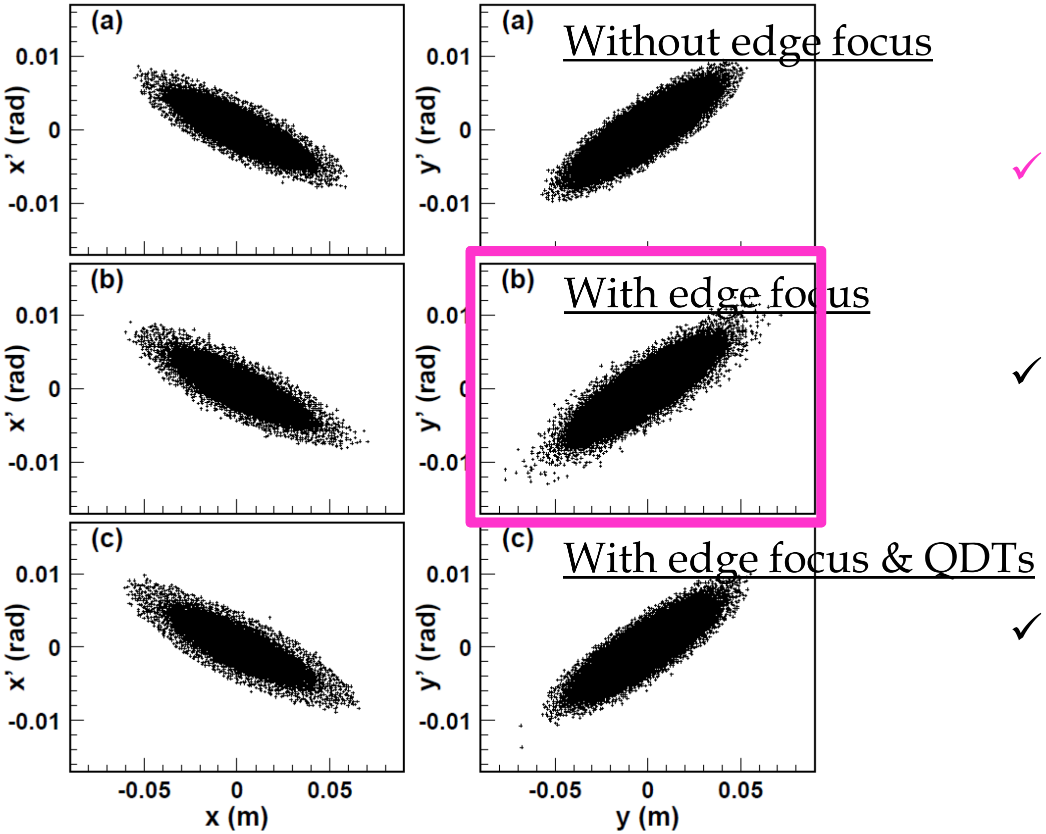

Numerical simulation by "Simpsons"




- ✓ The experimental result was well reproduced by numerical simulation.
- ✓ We investigated more detailed beam loss mechanism with the simulated result.

# Beam halo formation caused by the edge focus

Transverse phase space coordinates
at the end of injection calculated
with $\varepsilon_{tp}$=150$\pi$ mm mrad

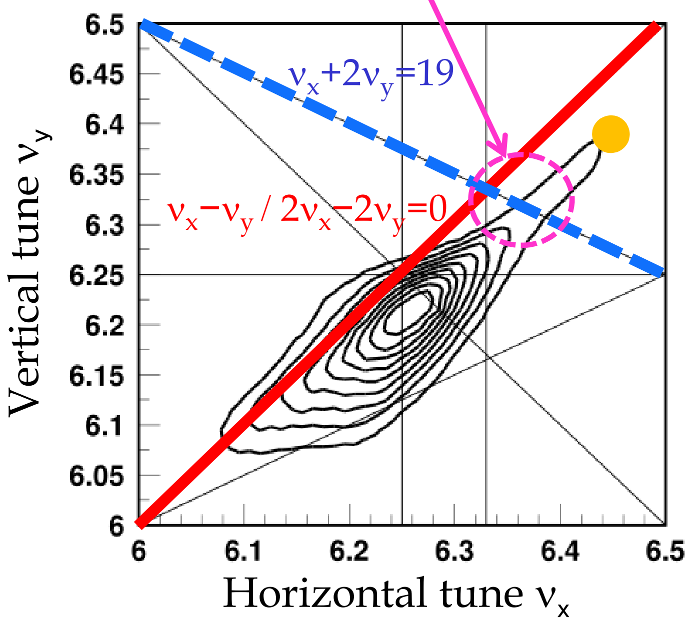



- ✓ The edge focus enhances beam halo formation especially on the vertical plane.
- ✓ The beam halo formation causes the extra beam loss observed when the transverse painting area is enlarged.
- ✓ The beam halo is well mitigated by QDTs, which results in the beam loss reduction achieved in this beam test.

# Tune diagram near the operating point

✓ The numerical simulation confirmed the beam halo is formed through the combined effect of two resonances;
$\nu_x+2\nu_y=19$ & $\nu_x-\nu_y$ / $2\nu_x-2\nu_y=0$.

✓ Particles on/near the resonances are the source of the beam halo.




◆ Random resonance : $\nu_x+2\nu_y=19$

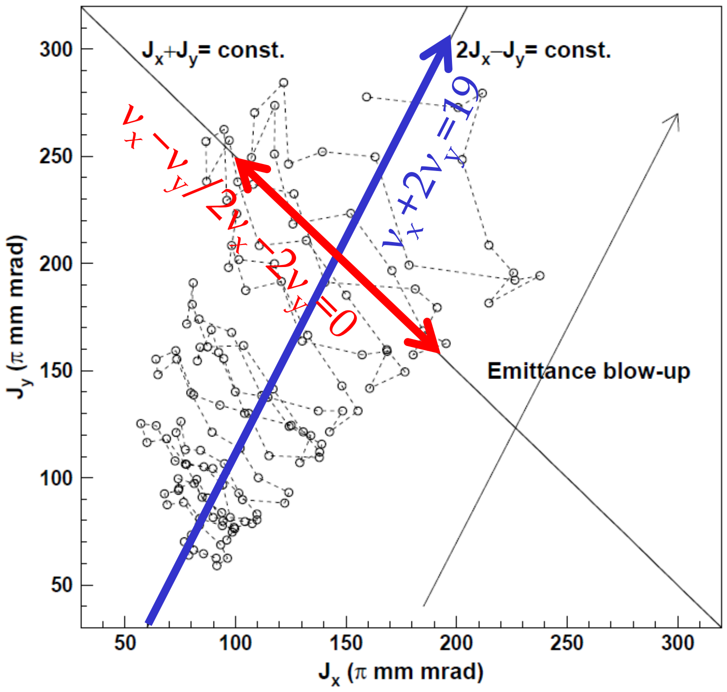
- arises from chromatic correction sextupole fields and an intrinsic sextupole field component in the main bending magnets.
- is additionally excited through a distortion of the lattice super-periodicity caused by the edge focus of the injection bump magnets.
- induces emittance growth on both horizontal and vertical planes with $2J_x-J_y$ =const.
- leads to two times larger emittance growth on the vertical plane than that on the horizontal plane.

◆ Systematic resonance : $\nu_x-\nu_y$ / $2\nu_x-2\nu_y=0$

- is excited by skew quadrupole errors, the 2nd order effect of sextupole fields, and an octupole component in the space charge field.
- induces emittance exchange between the horizontal and the vertical planes with $J_x+J_y$ =const.

# Typical sample of incoherent motion of one macro-particle that forms beam halo

2D plot of turn-by-turn betatron actions




Characteristic emittance blow-up that implies the combined effect of the two resonances, $\nu_x+2\nu_y=19$ and $\nu_x-\nu_y\ /2\nu_x-2\nu_y=0$;

✓ This analysis confirmed :

- Most of the beam halo particles are generated through such a single-particle behavior caused by the two resonances.

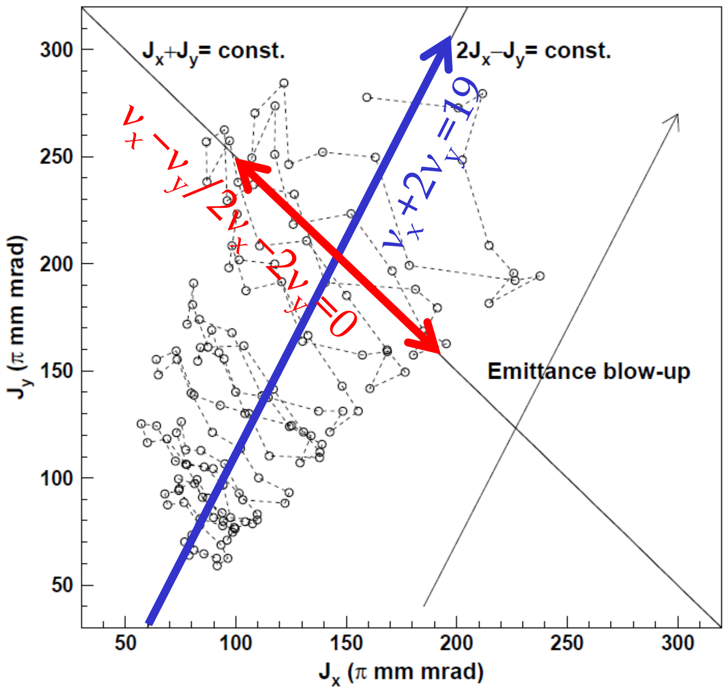
- The contribution of the $\nu_x+2\nu_y=19$ resonance is more critical for the observed extra beam loss, because the resonance causes more severe beam halo formation on the vertical plane.

- QDTs act to mitigate the $\nu_x+2\nu_y=19$ resonance through the recovery of the super-periodic condition, which results in the beam loss reduction achieved in this beam test.

✓ The horizontal and vertical actions gradually grow up along the line of $2J_x-J_y$=const., while oscillating in a direction parallel to the line of $J_x+J_y$=const.

# Possibility of further expansion of the painting area

2D plot of turn-by-turn betatron actions




✓ This analysis gave another important suggestion;

the further expansion of transverse painting area can be realized by reducing the effect of the $\nu_x$-$\nu_y$ / $2\nu_x$-$2\nu_y$=0 resonance, as well as mitigating the $\nu_x$+$2\nu_y$=19 resonance with QDTs.

Introducing "Anti-correlated painting", instead of "Correlated painting" used thus far

Anti-correlated painting has several advantages for mitigating the effect of the $\nu_x$-$\nu_y$ / $2\nu_x$-$2\nu_y$=0 resonance.

# Introduction of "Anti-correlated painting"

✓ In RCS, both correlated and anti-correlated painting are available.

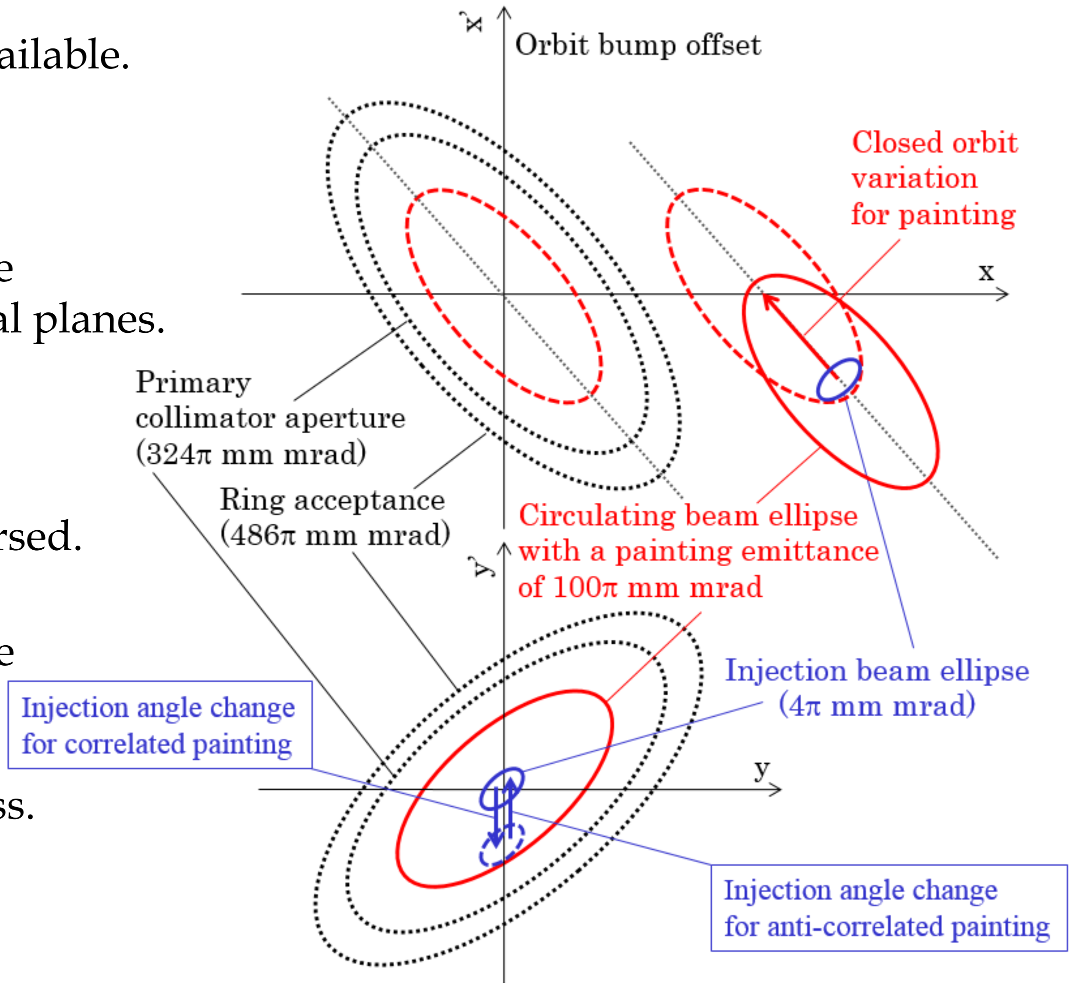
◆ Correlated painting:

the injection beam is filled
from the middle to the outside
on both horizontal and vertical planes.

◆ Anti-correlated painting:

the direction of the vertical
injection angle change is reversed.

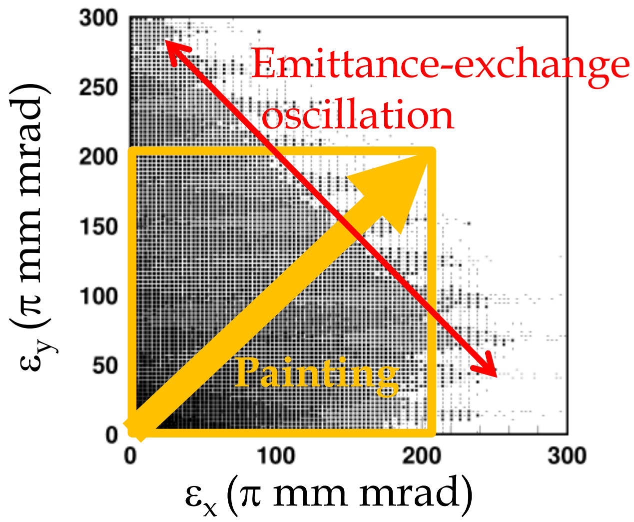
⇒ the injection beam is filled
from the outside to the middle
on the vertical plane,
in reverse to
the horizontal painting process.



## Correlated painting vs Anti-correlated painting

✓ Anti-correlated painting has several advantages for mitigating the effect of the $\nu_x$-$\nu_y$ / $2\nu_x$-$2\nu_y$=0 resonance.

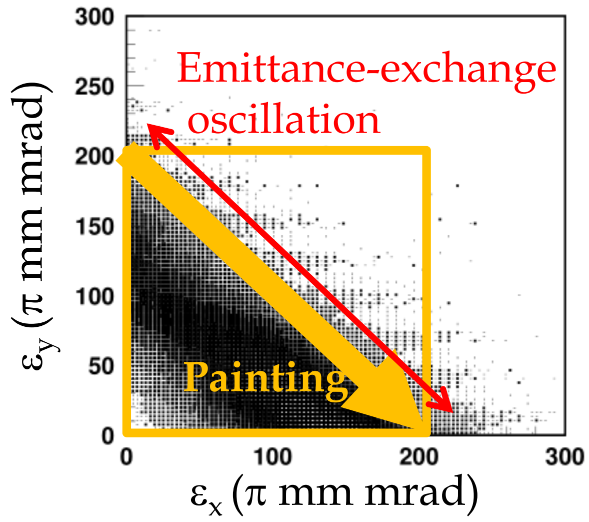
◆ Correlated painting




To the direction of beam painting, the emittance exchange caused by the $\nu_x$-$\nu_y$ / $2\nu_x$-$2\nu_y$=0 resonance occurs in the orthogonal direction.

The emittance exchange is directly connected to the emittance growth.

◆ Anti-correlated




Calculated @ the end of inj.

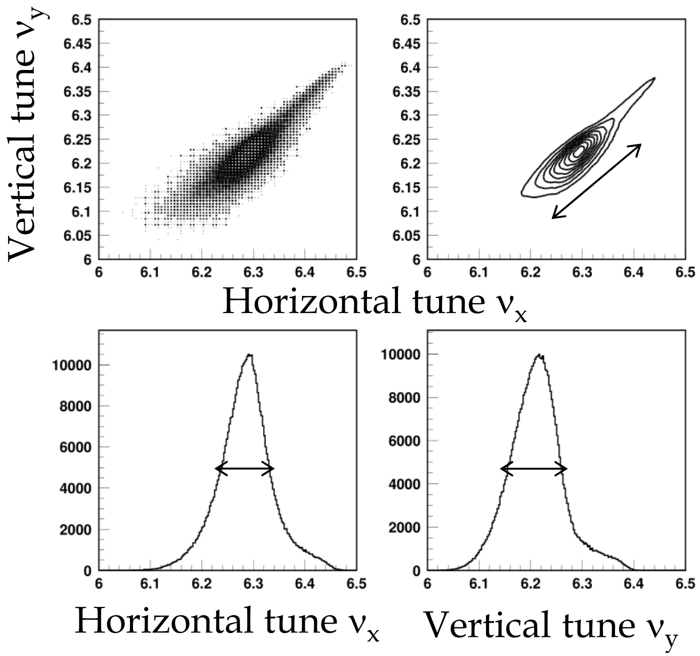
The direction of beam painting is the same as the direction of the emittance exchange.

The extra emittance growth by the emittance exchange is well suppressed.

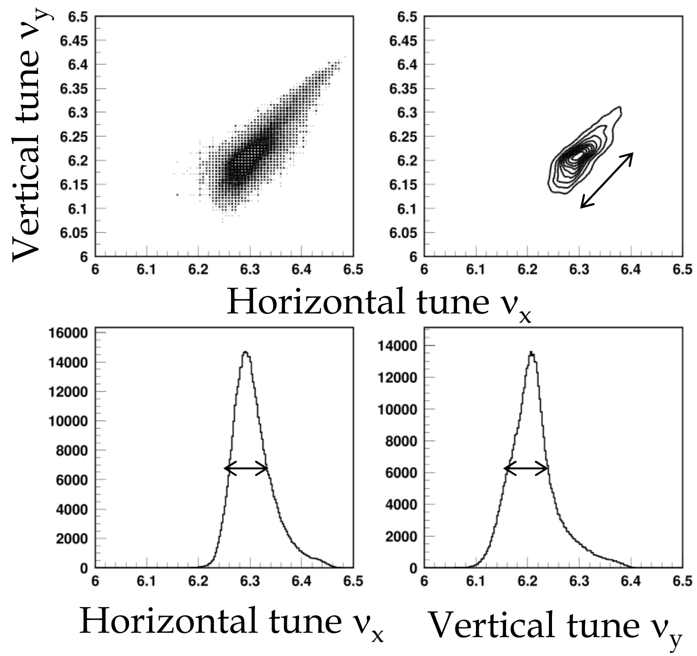
# Correlated painting vs Anti-correlated painting

- ✓ Another advantage of anti-correlated painting is to make a KV-like distribution.
- ✓ Thus anti-correlated painting gives less octupole component of the space-charge field.

◆ Correlated painting




◆ Anti-correlated painting




- ✓ Anti-correlated painting gives smaller space-charge tune spread than that in correlated painting; this means anti-correlated painting gives less octupole field component, leading to the mitigation of the $2\nu_x$-$2\nu_y$=0 resonance.

# Realizing 200π-mm-mrad transverse painting

Experimental condition

◆ Injection beam condition

Injection energy : 400 MeV

Peak current : ~45 mA

@ the entrance of RCS

Pulse length : 0.5 ms

Chopper beam-on duty factor : 60%

⇒ $8.4 \times 10^{13}$ particles/pulse,

corresponding to 1010 kW at 3 GeV

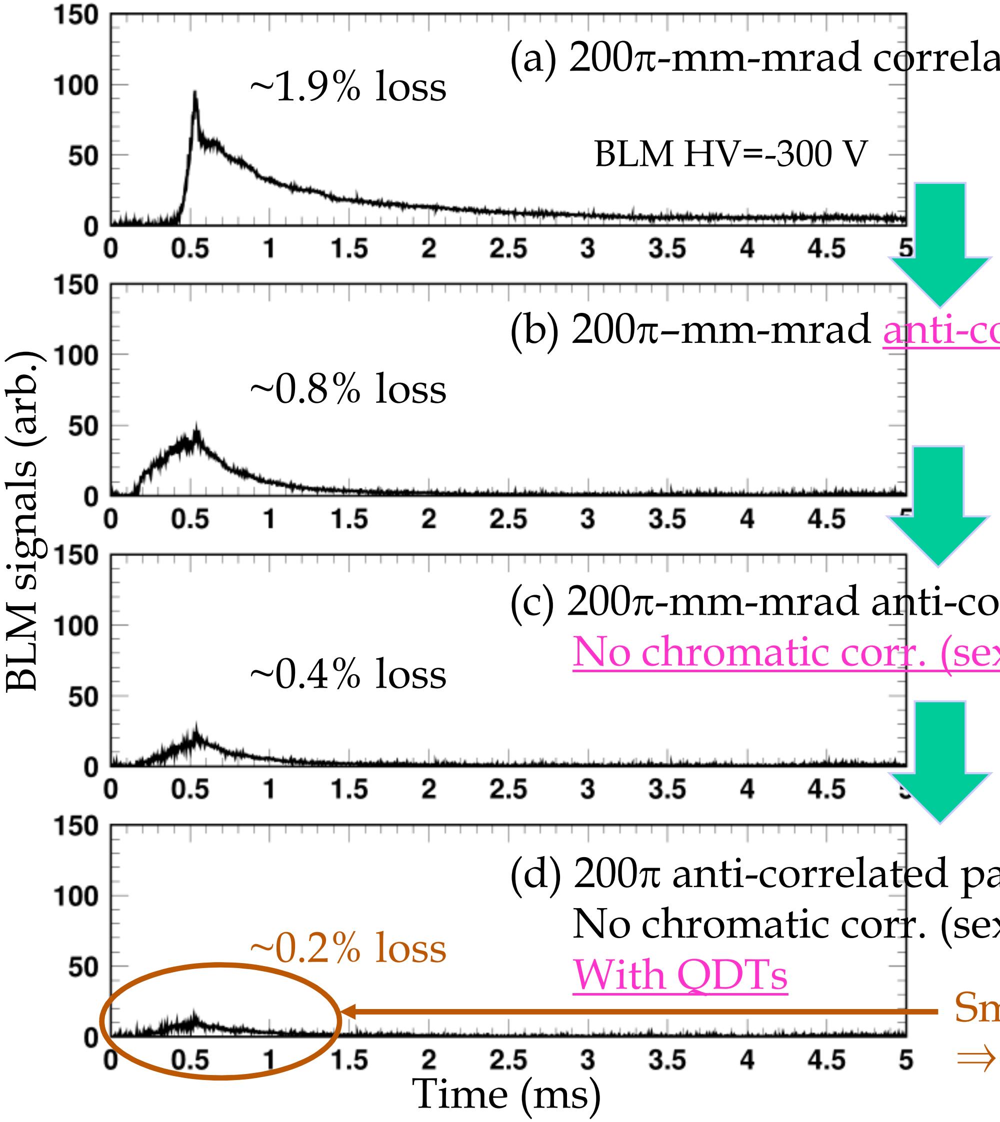
◆ Operating point;

(6.45, 6.38)

✓ Based on the above considerations, we tried to further expand the transverse painting area to 200π mm mrad for the 1-MW beam by using anti-correlated painting scheme as well as QDTs.

# 1-MW beam test with 200π-mm-mrad transverse painting

BLM signals at the collimator




By the mitigation of the emittance growth caused by the $\nu_x$-$\nu_y$ / $2\nu_x$-$2\nu_y$=0 resonance

By the mitigation of the $\nu_x+2\nu_y=19$ resonance

By the further mitigation of the $\nu_x+2\nu_y=19$ resonance through the recovery of the lattice super-periodicity

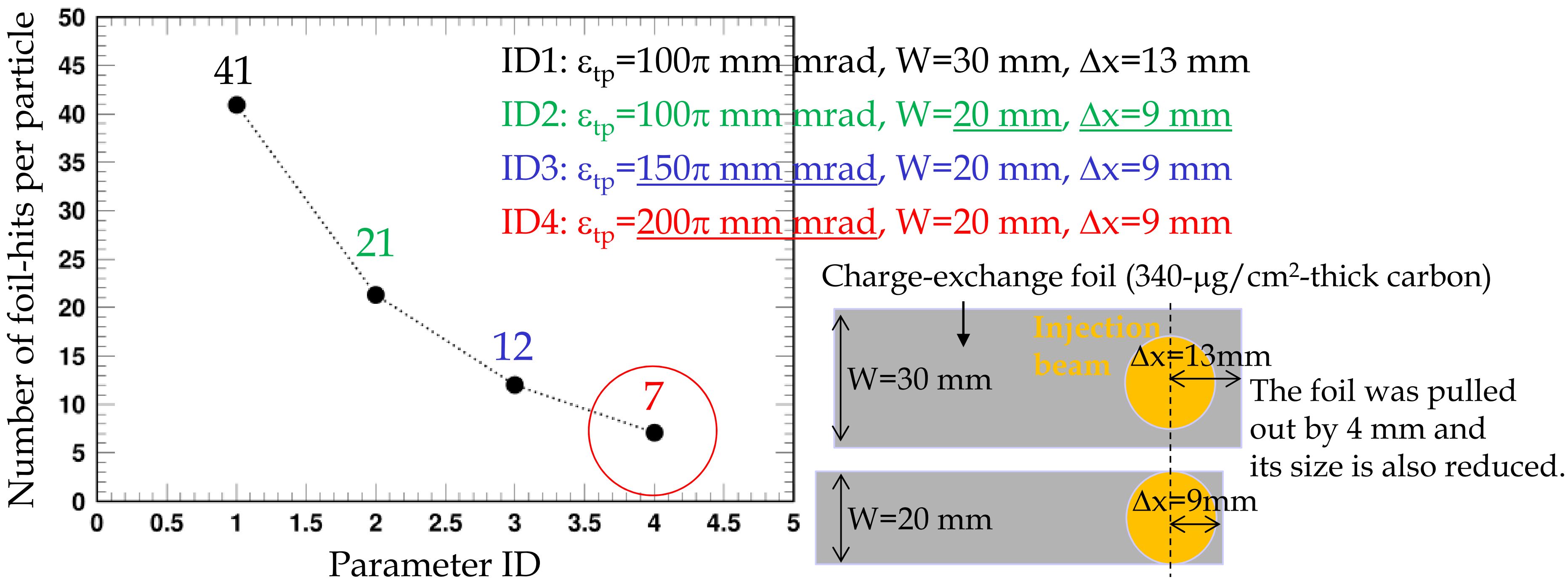
Small enough, localized at the collimator
⇒Controlled beam loss, not serious problem

✓ We recently got a good prospect of realizing wide-ranging transverse painting for the 1-MW beam by introducing both QDTs and anti-correlated painting scheme.

# Mitigation of uncontrolled beam loss arising from large-angle foil scattering

- ✓ By the recent efforts, un-controlled beam loss arising from large-angle foil scattering can be reduced drastically.

Parameter dependence of average number of foil-hits per particle




- ✓ This reduced number of foil-hits expects that the machine activation near the charge-exchange foil is kept at << 10 mSv/h on the chamber surface even for the 1-MW beam operation, which is sufficiently within the acceptable level.
- ✓ Through these series of recent beam tests and numerical simulations, the beam loss for the 1-MW beam was finally reduced to the permissible level.

## Summary

- We re-started a 1-MW beam test in October 2015 after the RF power supply upgrade.
- Longitudinal beam loss was completely removed by beam loading compensation conducted after the RF power supply upgrade.
- Transverse beam loss, such as space-charge induced beam loss, was also well minimized by transverse and longitudinal injection painting.
- The remaining beam loss is now mainly from foil scattering during charge-exchange injection.
- Beam instability was also well suppressed by controlling the chromaticity and the tune variation during acceleration.
- Recently, we got a good prospect of doubling the transverse painting area by introducing both QDTs and anti-correlated painting scheme, by which uncontrolled beam loss arising from foil scattering can be reduced drastically.

- By such recent efforts, the 1-MW beam operation is now estimated to be established within the permissible beam loss level.
- Though the routine output beam power is now temporarily limited to 200 kW due to a malfunction of the neutron production target, RCS beam commissioning itself is making steady progress toward realizing the 1-MW design beam operation.
- The further parameter optimization for the 1-MW beam will be continued with more careful attention to beam quality as well as to beam loss.